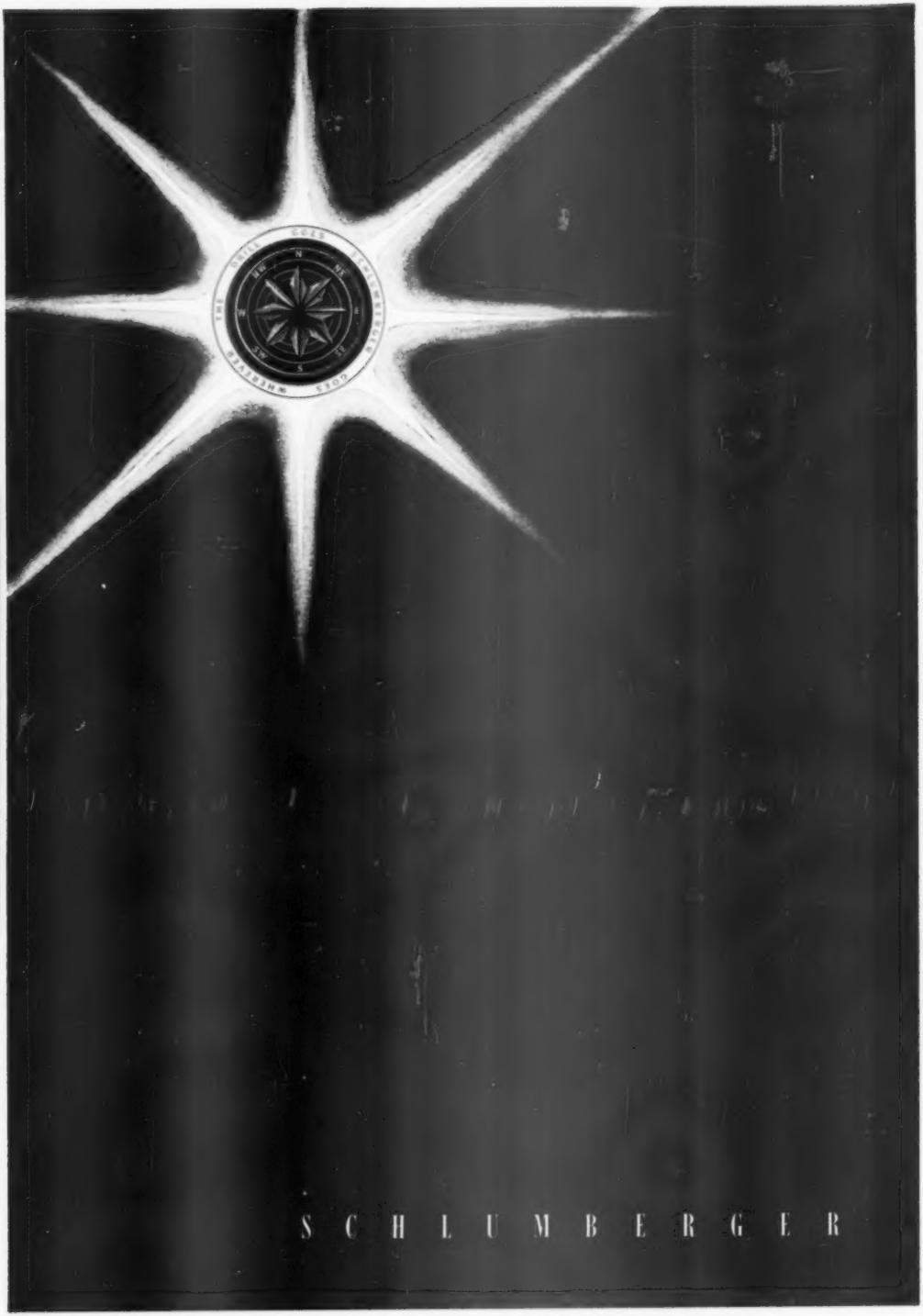
JOURNAL OF

Petroleum Technology

DECEMBER, 1951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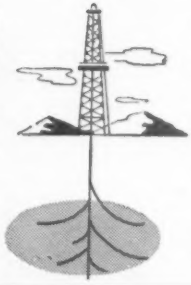

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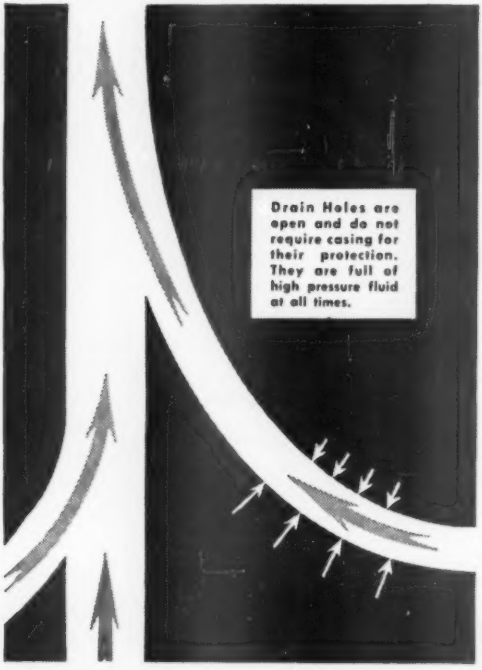

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Journal of Petroleum Technology is published monthly. Domestic Subscription: North, South and Central America, $8; foreign, $9; to AIME members, $6, or $4 if in combination with subscription to either Journal of Metals or Mining Engineering. Single copies 75 cents; special issues, $1.50. Registered cable address AIME. Printed in USA.

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Official Publication

Petroleum Branch

American Institute of Mining & Metallurgical Engineers

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Journal of Petroleum Technology is published monthly by the American Institute of Mining and Metallurgical Engineers at 29 West 39th Street, New York 18, N. Y. Entered as second class matter January 31, 1949, at the post office at New York, N. Y., under the Act of March 3, 1879. Additional entry at Dallas, Texas.

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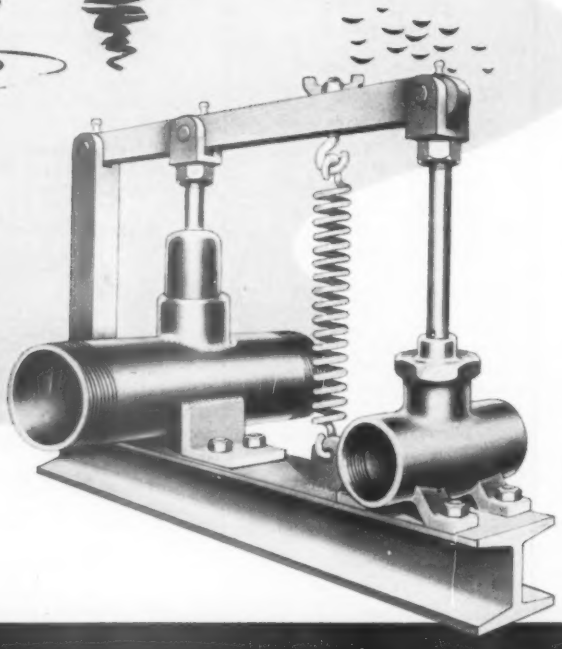

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THE PROFESSIONAL MAGAZINE FOR PETROLEUM ENGINEERS

Journal of Petroleum Technology

Vol. III DECEMBER, 1951 No. 12

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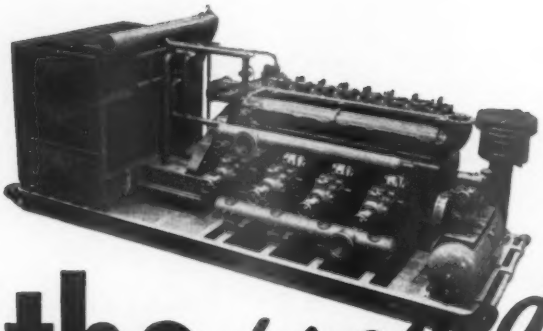
On the Cover — December's snow-covered ground and rare, crisp atmosphere may be found almost the year around on the axis of the Madden Anticline near the Owl Creek Mountains in Fremont County, Wyoming. Here, a plane table crew works to locate a drilling site for the Carter Oil Co. Photo by Standard Oil Co. (N.J.)



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A West Coast Consultant Reviews the Broader Current Trends Of Our National Fiscal Policies and Draws Some Specific Conclusions Regarding

THE EFFECT OF TAXATION IN THE OIL INDUSTRY

By W. H. Geis
Member AIME

WHEN the effect of taxation in the oil industry is considered, no assumption is introduced that the effect is different when applied to oil than when applied to any other industry. All industry or business is affected in more or less the same general manner. The difference, if any, is largely in degree. However, there are basic differences between the industries themselves which may cause a tax, even when uniformly applied, to vary in its severity and thus to create in a particular industry serious problems which, perhaps, are not developed in some other industry.

Today our most severe tax is the Federal income tax, although by no means is it the only severe tax. Apparently, it is assumed that income taxes are uniformly applied between corporations and between individuals. Nothing could be further from the truth. The present scheme for levying income taxes is based on class legislation — one of the very things which the founders of this country endeavored to prevent.

The Constitution, written by men who had suffered tyranny through taxation, originally provided that direct taxes must be apportioned among the several states according to their respective numbers. For 137 years, this provision guaranteed uniform taxation under which the United States prospered and became a great and powerful nation.

Sixteenth Amendment

The Sixteenth Amendment gave Congress the power to collect taxes on income from whatever source derived without apportionment among the several States and without regard to census or enumeration. At the time no one could possibly have foretold the use to which the Federal power to lay direct taxes on the people would be put. Consequently, the people accepted the income scheme of taxation as a rather good method of allocating taxes. It would, indeed, have taken a most far-seeing individual to have forecast that the power granted by the Sixteenth Amendment would in a few short years be used by a determined group of socialistic planners to progressively acquire control over all industries as well as restrict the personal liberties of the people and to create an all-powerful Federal State.

Woodrow Wilson, who was president when the Sixteenth Amendment became effective, was, however, a far-seeing individual and he apparently understood the risks, and warned:

> "The history of liberty is the history of the limitation of governmental power, not the increase of it. When we resist concentration of power, we are resisting the processes of death, because concentration of power is what always precedes the destruction of human liberties."

This paper was presented at the Petroleum Branch, AIME, Fall Meeting in Los Angeles, Calif., Oct 25-26, 1951.

Reading the Sixteenth Amendment carefully will show nothing therein, at least from a layman's viewpoint, which permits Congress to levy non-uniform income taxes or to levy direct taxes on anything other than income. The writer can see nothing in the Sixteenth Amendment which permits Congress or the Treasury Department to levy a 90 per cent tax on one man's income and a ten per cent tax or no tax at all on some other man. There is also nothing in the Sixteenth Amendment which would permit Congress to levy a tax upon capital, and yet it is the capital of the natural-resource industries, and particularly the capital of the oil industry, which is being taxed under a trumped-up definition that classifies the return of capital as income.

Therefore, income taxes as now levied are the result of class legislation.

This does not imply that the present scheme of income taxation is either socially good or bad, but only that it is non-uniform and classified as between individuals and industries. Thus it happened that the impact of taxation is not the same between industries; some are hit hard; some not so hard; some are able to survive and some have a future that can only end in bankruptcy. The unfortunate part appears to be that such effects are created by a tax scheme said to be uniformly applicable to all.

Many persons fear that under the present and prospective tax laws within the producing branch of the oil industry this branch must eventually succumb because its capital is being taxed away and net income, if there is any, no longer belongs to the corporation or individual who earned it but the major proportion belongs to the government. However, it will be noted that if there is no net income, the government does not share in the losses. In other words, a business can go broke with ease, but if it dares to be successful, the present corporation taxes run up to 70 per cent for the Federal government alone, while taxes on individuals are as high as 90 per cent plus.

Control of All Profits

The approach of totalitarianism, whether of the socialistic or communistic variety, apparently is always first marked by the lack of necessities at the retail level. This lack inevitably results in a system of price fixing, rationing, and an iron-handed, non-competitive governmental control over everything. Today the oil industry is experiencing the first pangs of such control, but it may not recognize the implications of the situation. We should not be fooled, particularly when the executive

head of our government in his mid-year message to Congress definitely stated the objectives of the government. President Truman came out flatly for government control of all business profits. This, he said, should be the basis for regulating prices. The philosophy involves the draining away of the resources of the people, but when government in assessing such taxes goes beyond its proper constitutional functions, nothing productive is contributed in return, but more regulation, more regimentation, and more taxation.

Although the road to socialism is smoothed by many devious governmental actions, a great solicitude for the welfare of the people is expressed. Secretary of the Treasury Snyder insists that the people be thrifty and secure their future through the purchase of more government bonds. He says not one word about the necessity for the government to practice a bit of thrift along with the people.

Resistance to the extravagant governmental expenditures finds only a very few supporters in Congress. Only a handful of senators and representatives followed the lead of Senators Douglas, George, and Byrd, of the Administration's party, in trying to wring even a little water from the Federal budget which now approaches $95 billion a year.

Why is it that after the Hoover Commission showed in its report by 300 recommendations where $5,400,000,000 per year could be saved simply by better governmental housekeeping, the present Congress has adopted only one of the 300 recommendations?

Many of the fiscal policies, particularly the taxation policy, of the present government are said to be necessary in order to prevent further inflation. However, the government bought five million pounds of oleomargarine at 25½ cents per pound and at the same time sold 5,500,000 pounds of butter, the more expensive product, at 15 cents a pound to a foreign government and charged the difference to the American taxpayer.

Also the government recently purchased 68 million can openers. Was it or was it not inflationary for the government in a nine-month period to buy 1,917,000 pounds of black pepper? Why also was it necessary, with 1,500,000 in arms, to purchase 11,735,000 pairs of combat boots and to demand delivery in such a limited period of time that the said boots rose from $7.82 a pair to $16 a pair? These are only a few examples of the scare buying by the government, and yet it claims that the people's purchasing power must be drained in order to prevent inflation. The truth of the matter is that inflation as a national policy was deliberately adopted by our government.

Expenditures Through the Years

If we are to understand the effects of taxation on industry and on the oil industry, we should at least have some concept as to the amounts of money spent by the Federal government. At times in the past our government has been up against heavy expenditures. Some of these periods have been as follows:

The Lincoln Administration cost $3,252,000;
The McKinley Administration $2 billion;
President Wilson spent $47 billion;
Coolidge and Hoover combined spent $34 billion;
Roosevelt in his first eight years spent $67 billion.
Excluding the cost of the last World War, the total Federal governmental expenditures from George Washington through the year 1940 amounted to $179,620,000,000.
The Truman Administration for the fiscal year 1946 through September 1949, had spent $191 billion, which is some $12 billion more than the total cost of all past governments starting with Washintgon.

But, that isn't the end of it. The Congress which just adjourned appropriated $95 billion which of course will be spent by this administration. It can be estimated that since 1946 and to the end of the present term, the amount spent will approximate $360-$375 billion, more than twice the amount spent by all past administrations starting with Washington. Can anyone believe that the expenditure of such a vast amount of money does not have a serious effect upon industry and upon the people? Bear in mind that these huge expenditures and the deficit which has resulted therefrom comes at a time when the income to the government extracted from the sweat and toil of the taxpayer is at a near record peak. But, as it now stands, neither the government nor the taxpayer can make ends meet — and both go broke.

Government propaganda advises that our crushing burden of taxation results from the military expenditures made necessary in protecting this country. However, let us again look into the facts.

In 1930, the non-military expenditures of the Federal government amounted to $2,700,000,000, whereas last year the non-military expenditures were $27,800,000,000, which is more than ten times the former figure. This year we can be prepared for a non-military bite approaching $30 billion and, in addition, there are a great many expenditures charged to military expediency which are nothing more or less than logrolling disguised to quiet complaint. Now, we may ask if the government in 1950 was ten times as useful to the people as it was in 1930. Plainly, of course, it is not, but it is going to cost $27 billion or $30 billion per year for non-military expenditures so long as the spending thereof gets the votes to perpetuate the spenders in power.

In 1950 the Federal corporations which are in competition with private industry had losses and hidden costs of more than $19 billion. For example, take the Tennessee Valley Authority, which so far has cost the taxpayers somewhere around $1 billion. Part of the hidden costs included charges made by the TVA in order to cover up its inefficiencies amounting to $150 million charged to flood control, and another $150 million or so charged to navigation. By such means are the real costs covered up, and yet we have the statement of C. J. Green, former accountant for the Federal Power Commission, who advises that if the TVA kept its books as private corporations are required to, that its real costs of producing electric energy would be prohibitive and about twice what was charged by the private utilities which the TVA forced out of business.

The Federal corporations, such as the TVA, pay no taxes and have no capital costs and apparently are responsible to no one. In contrast, in the year 1949, the private electrical utility industry paid taxes amounting to $803 million which, incidentally, was an increase of 150 per cent compared with what they paid in 1939.

Petroleum Industry Finances

Now, in comparison with the irresponsibility and the losses of the Federal corporations such as the TVA, let us see the financial situation that an active oil company is up against. This particular example uses one of America's largest oil companies, a company which in 1948 had a gross income of $1,073,000,000. Although this company has a large crude oil production of its own, it nevertheless bought from others — mostly independent oil producers — $407,902,000 of crude oil and products. In running the company, including the cost of transporting the oil purchased and for materials and supplies, it paid $200,863,000. It paid in wages and salaries $164,683,000, which, incidentally, included $23,879,000 for employees'

benefits. It paid $45,574,000 as interest on its bank loans and on its outstanding bonds and preferred stock. After deducting these costs it had left about $154,426,000 before any capital expenditures in the expansion of its own business. It paid $78,729,000 in taxes excluding all sales taxes. Thus, taxes on this private corporation took 51 per cent of the net profits. Dividends on the common stock amount to $34 million, so the government in taxes got 2.6 times as much as did the owners of the corporation. Bear in mind that this was for the year 1948 when tax schedules were much lower than they are at the present time. At the same time this company was forced to act as a tax collector for the government, and it collected an estimated $282 million additional in taxes from other parties, bringing the total responsibility for taxes on this company in one year to $360 million. However, comparatively, this company got off rather easy.

The oil industry, irrespective of what is said to be a favorable tax position due to depletion, is one of the most heavily taxed industries in the country. The oil industry represents three per cent of the national income, but pays seven per cent of the Federal, State, and local taxes. The oil industry is subjected to tax levies from 180,000 separate tax jurisdictions in this country. As a result of the multiplicity of such taxes, it has been estimated that the oil industry's total tax bill for the year 1950 amounted to $3.5 billion. For the same year the total value of the crude oil production taken from the wells amounted to $5 billion. The industry's tax bill was 70 per cent based on the original value of the basic production. The total value of all the refined products in 1950 amounted to $8 billion. The tax bill on this basis amounted to 44 per cent of the gross value. However, in addition to carrying this burden of taxation, the oil industry in the same year drilled the greatest number of wells in its history, plowed back $2 billion of its earnings in capital expenditures, and expended $100 million in research in order to provide the public with better products at lower costs.

It can be calculated that if all the oil-producing companies in the United States were allowed the 27½ per cent depletion on their gross income the return of capital would amount to $1,375,000,000. This indicates that the capital requirements of the industry are not balanced by some $700 million per year. If the true depletion allowance were available, it is reasonable to believe that the capital requirements of the industry over and above the depletion allowance amounts to some $1 billion per year. The overage is taxed as income, but must be made up out of earnings after taxes. And the earnings after taxes are not sufficient to carry the load. The larger companies may perpetuate themselves for a time through the issuance of bonds and preferred stock, but the smaller producing companies find themselves in an impossible position with little or no possibility for expanding and with no remaining incentive to continue in the oil production business. This is not a conclusion on the writer's part, for it is subject to definite mathematical analysis.

During the course of the past year some $150 million of independent production has been sold in California. At the present time there are pending sales involving additional millions of dollars. Why are these independents after outstanding success in the oil business now hastening to sell out? The reason is quite clear.

Consider, for example, that a company has a million-barrel reserve. It is producing this reserve in the normal course of its business and sells and collects for the oil monthly. In such a case it possibly is allowed 27½ per cent depletion, and then after paying the royalties and the lifting costs the net income is subjected to income taxes as high as 70 per cent, since all of the revenue after costs and depletion is classified as income. However, if, on the other hand, it sells its million-barrel reserve not by months, but sells it all at one time, then the value of the oil is classified as capital, which it is, and the owner is subjected to only a 25 per cent capital gain. When large volumes of oil are involved, this becomes of transcendent importance.

Profits Per Barrel

In order to show the situation more clearly, let us take a single barrel of average California oil which sells for $2.40 per bbl. After paying royalty, the operator has $2 a bbl; after paying lifting costs of 50 cents per bbl, he will have left $1.50. This is classified after depletion as net income for tax purposes and carries a probable federal tax of 70 per cent, or 67 cents per bbl in taxes. However, every barrel in the reserve is not going to be produced today, and since it is to be produced in the future, the value of the oil to the operator today is only 76 cents after costs and depletion.

Actually, after taxes, the operator earns 9 cents a bbl. He possibly retained 54 cents per bbl as depletion, so he has left 63 cents a bbl. However, if the said barrel of oil were included in the sale of the total oil reserve, after deducting the lifting cost of 50 cents per bbl and paying his capital gains tax, he can retain for himself $1.13. The difference between selling out and producing the oil amounts to 50 cents per bbl. If the said operator produces one million bbl of oil, he may eventually, over a period of time, retain $630,000 but if he sells it he can retain $1,130,000, a difference of $500,000 to him on each one million bbl sold. Is it, therefore, any wonder that the independents are selling out?

The foregoing illustration involves production by a corporation. However, a recent sale in California was made by an individual oil producer. This particular producer has been eminently successful and had a net income from his oil properties of approximately $1 million per year. Ordinarily, an individual in this situation would be considered most fortunate. However, due to his large income and because of Federal and State income taxes alone, he found himself in the 94 per cent income tax bracket. In other words, he could keep for himself only 6 cents out of each dollar of net income. From his million-dollar-per-year income, he could retain only $60,000 a year. In this particular case, it took more than the amount retained from depletion in order to maintain his production and the new wells drilled did not add to the reserve, but simply served to lessen the rate of decline. It worked out that the man had a reserve of approximately 10 million bbl which would be completely depleted in approximately 12 years. If he were able to retain the $60,000 per year and earned it for 12 years, he eventually would end up with $720,000 after taking all of the risks. The property was eventually sold at $1.05 per bbl in the ground, yielding to the owner a gross of $10,500,000, and after taxes he retained in cash $7,875,000. I am sure that no one would wish to dispute the fact that this particular individual was forced to sell his property because of taxes. This is the principal effect of taxation in the oil industry.

The examples I have cited can be multiplied a hundredfold all over this country. The result is that from the production standpoint the larger companies are getting larger and the smaller companies are being eliminated. The Department of Justice can scream all its wants to about monopoly in the oil business, but if anything is pushing it toward monopoly it is the ridiculous tax scheme used by the Federal government by classifying the return of capital within the oil industry as income and then levying outrageous taxes on that income. ★

Mexican Oil Industry Looks Ahead

Reported by W. B. Davis

Mid-Continent Section

E. E. BARBERII

Mexican oil production is on the rise and daily output is expected to be doubled within the next eight years. This outlook of that country's production future was given by E. E. Barberii before a meeting last month of the Mid-Continent Section of the Petroleum Branch, AIME. Barberii did engineering work for Creole in Venezuela from 1944 to 1947 and was an editor of *Petroleos Interamericanos* from 1947 to 1949. Since 1949 he has been assistant professor of petroleum engineering at the University of Tulsa.

The management of Petroleos Mexicanos (Pemex) is optimistic about producing 500,000 B/D and exporting 160,000 B/D by 1958. Current oil production amounts to 230,000 B/D and daily exports of crude oil and refined products total approximately 80,000 bbl.

Future increases in production are expected from new discoveries, and the optimism of the management is based on the vast geological and geophysical studies that the organization initiated in 1942 when the exploration department was fully organized. Since 1942 some 8,540,000 acres of prospective oil territory have been covered by geological and geophysical parties representing a grand total of 2,875 months-crew.

Present Mexican refining capacity amounts to 198,350 B/D, and Pemex is extending its pipe lines and locating new refineries at key points in order to supply more adequately the demands for refined products in all sectors of the nation. The total daily sales of refined products, LPG, and natural gas within the country averages $540,000. The revenue from exports is designated to obtain the necessary oil country equipment in U. S. and European markets.

Pemex has 87 drilling rigs, and has ordered eight more rigs from U. S. manufacturers. Current programs call for acceleration of drilling activity in the Isthmus of Tehuantepec, where it is expected to have 24 strings running by January, 1952.

The Isthmus, which is also called the Southern Zone, has an area of 110,000 square miles. This zone comprises the states of Campeche, Chiapas, Tabasco, Quintana Roo, Yucatan, part of the state of Oaxaca, and the southmost part of Veracruz, the latter being the nation's most important oil producer.

Recent discoveries at Rabon Grande, Jose Colomo, Fortuna Nacional, and the Francita area are making the Southern Zone one of the most important exploratory areas to watch in Mexico.

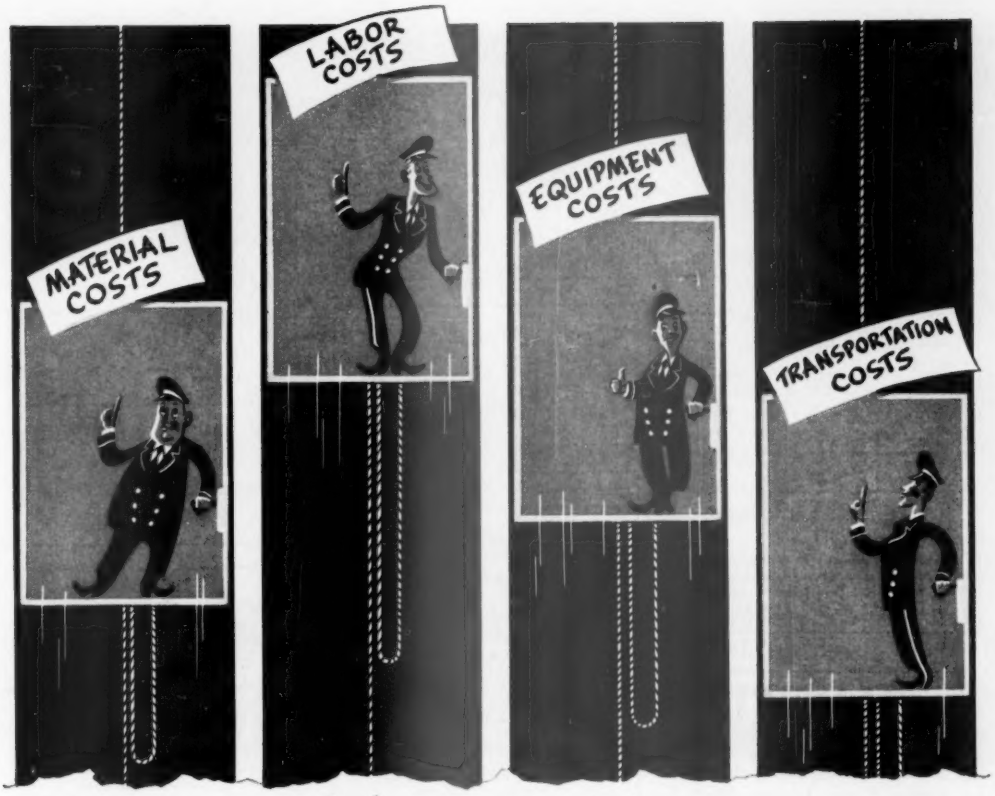
Pemex reactivated the search for more oil in the Isthmus by increasing production in El Plan-Field, through the finding of new producing horizons and deepening of wells. Present daily output of the Southern Zone amounts to 22,000 bbl.

To accelerate exploratory drilling in the Southern Zone, Pemex has invited foreign firms to participate. Two American companies, CIMA and the Isthmus Development Co., are currently doing exploration work there. CIMA found the Xicalango gas field in Campeche, and also the Tortuguero structure and Rabon Grande Field in Tabasco. At this time it is too early to evaluate the operations started by the Isthmus Development Co.

Agreement between Pemex and these companies provides that: (1), if production is found, 50 per cent of the value of that production will be set aside to reimburse the expenses incurred in drilling; (2), for 25 years, the contractor shall receive 15 per cent of the value of the production obtained from inland pools as a bonus or 18⅔ per cent from offshore production; (3), the contractor will hand over to Pemex every productive well duly completed and from there on Pemex assumes responsibility for the management of the well; (4), drilling practices and completion programs are the responsibility of the contractor. However, common understanding on these matters between Pemex and the contractor is required; (5) the contractor assumes all expenses at his own risk.

The desire to bring the drill to the several structures uncovered as soon as possible is due to greater demands for oil and the high degree of industrialization that Mexico has experienced during the last 15 years. It is estimated that by 1955 the nation will require some 240,000 B/D. ★ ★ ★

SOUTHWEST TEXAS SECTION OFFICERS for 1952 are, L to R, Harry D. Vaughan, Lane-Wells Co., chairman; Barrett Booth, Houston Oil Co., vice-chairman; and Joseph B. Woodward, Seaboard Oil Co., secretary-treasurer. Also elected at the November meeting of the section in Corpus Christi were the following directors: Charles Barnes, Texas Acidizers; R. E. Bates, Sun Oil Co.; R. J. Granberry, Core Laboratories, Inc.; J. T. May, The Chicago Corp.; T. E. Keefer, Stanolind Oil and Gas Co.; R. B. Sale, Seaboard Oil Co.; Don F. Shaw, Humble Oil and Refining Co.; W. J. Turner, Sun Oil Co.; Lee J. Thronson, Sun Oil Co., retiring chairman, will also be a member of the Board.



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In short, science and invention have become so complex that a man with an idea for a better product often needs the assistance of an army of specialists and millions worth of equipment to prove his idea has value.

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How to proceed: Instructions on how to submit ideas under the Sinclair Plan are contained in an Inventor's Booklet available on request. Write to: W. M. Flowers, Executive Vice-President, Sinclair Research Laboratories, Inc., 600 Fifth Avenue, New York 20, N. Y. for your copy.

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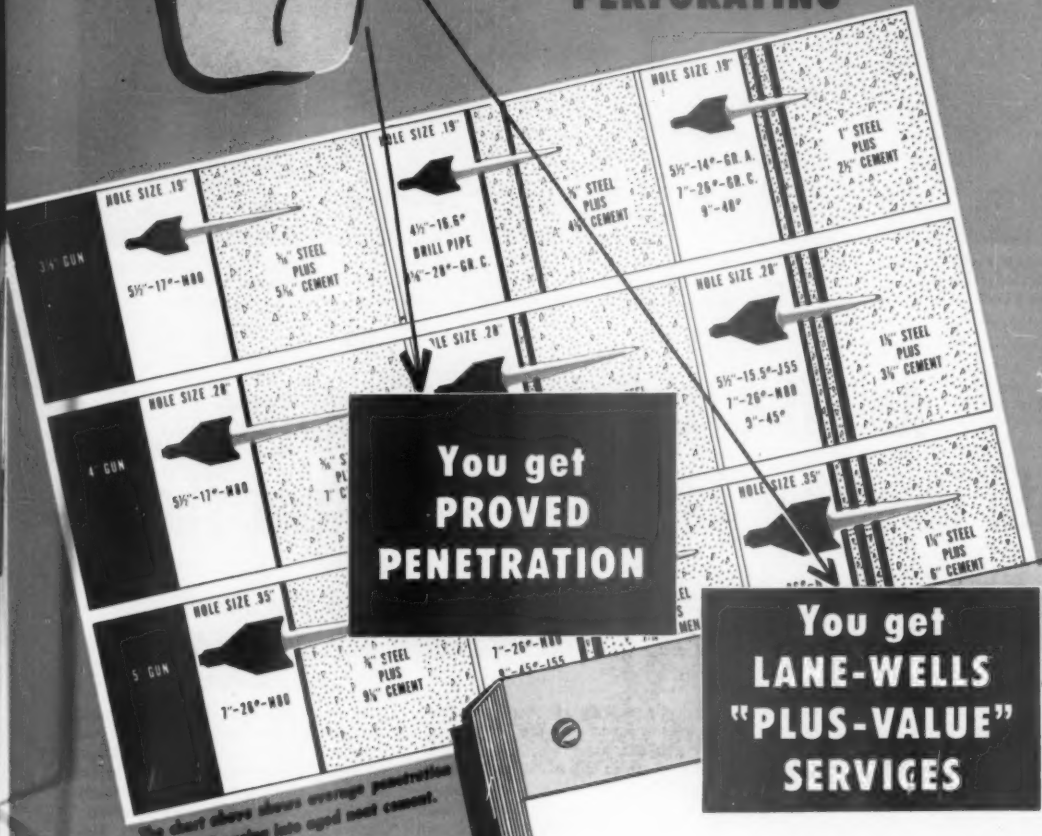

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THE EFFECT OF WITHDRAWAL RATE ON THE UNIFORMITY OF EDGEWATER INTRUSION

M. MUSKAT, GULF OIL CORP., PITTSBURGH, PA., MEMBER AIME

ABSTRACT

Calculations are reported on the differential sensitivity of the updip invasion of oil strata of varying permeability to the driving pressure differential. It is assumed that the water-oil interfaces advance with sharp fronts, or that the microscopic displacement efficiency is independent of rate and capillary pressure effects. It is found that, under such conditions, limitations of withdrawal rates will not greatly inhibit the "fingering" and bypassing tendency through high permeability strata unless the differential fluid head across the original oil column is of the order of or exceeds about 80 per cent of the driving pressure differential. In practice, such restrictions will be feasible only for oil reservoirs and aquifers of high permeability and dip, but may develop automatically under combined gas injection and water drive operations.

INTRODUCTION

A commonly expressed view regarding the intrusion of edgewaters into oil producing formations is that the geometry of such advance is rate sensitive. Specifically, it has been suggested that high rates of advance, stimulated by rapid withdrawals, will lead to "fingering" and an irregular type of invasion, whereas at low withdrawal rates the water encroachment will be more uniform. Two factors tend to support this view. One is the resultant effect of capillary pressure and gravity gradients in the displacement processes[1] involved in water intrusion, which are magnified at low rates of flow so as to improve the recovery efficiency. The other is the direct retarding effect of the rising water head as it advances upslope into the producing area.

Capillary pressure forces give rise to a rate sensitivity of the oil recovery by water displacement in uniform strata as well as differential effects in non-uniform formations. These are basically independent of the effect of gravity and would also occur in horizontal beds or when the oil and water have the same density. Unfortunately, however, the fundamental equation describing the displacement process under the action of capillary pressures can be solved only by numerical or graphical procedures, and moreover the solutions are sensitive to the character of the capillary pressure and relative permeability curves.* On the other hand, the direct effect of gravity can be given a formal analytical solution if the simplifying assumption is introduced that the water advances with sharp fronts in the individual uniform strata. It depends on the absolute permeabilities of the water invaded zones and hence results in a rate sensitivity of the differential invasion in stratified media. Although a treatment of this factor alone will not give a complete evaluation of the effect of rate on water intrusion in non-uniform pays, it should provide at least a semiquantitative measure of the sensitivity of "fingering" to withdrawal rate. Such a treatment will be presented in the following sections.

GENERAL THEORY

The basic element of the theory is the history of water advance updip in a uniform stratum (Fig. 1). In contrast to the assumption of constant flow rate, generally made in the analysis of displacement processes, we shall assume here that

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch May 28, 1951. Paper presented at the Fall Meeting of the Petroleum Branch in Oklahoma City, Okla., Oct. 3-5, 1951.

*The complexity of the quantitative treatment of oil displacement by water when including the capillary pressure terms is well illustrated by the recent work of J. C. Calhoun, Jr. and J. W. LaRue (Producers Monthly, April, 1951, 15, 20-29) in which the numerical analysis had to be limited to approximate evaluations of the *type* of effects to be expected (*cf.* also S. J. Pirson, *Elements of Reservoir Engineering*, Chapter 6).

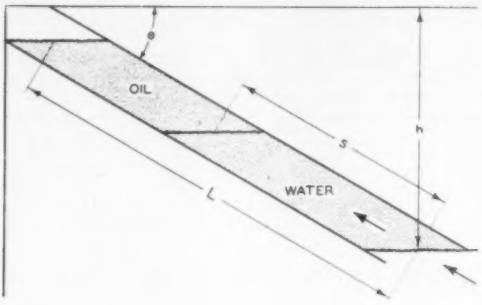

FIG. 1 — DIAGRAMATIC REPRESENTATION OF WATER INVASION UP-DIP INTO AN OIL PRODUCING PAY.

the driving pressure or fluid head differential is constant. Denoting the mobilities (effective permeability to viscosity ratios) behind and ahead of the water-oil interface to have the constant values m_w and m_o, it may be shown by straightforward application of potential flow considerations that the rate of advance of the interface will be given by the differential equation:

$$\frac{G}{1-\overline{m}}\frac{dx}{d\bar{t}} = \frac{1-Gx}{1-(1-\overline{m})\,x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where:

$$\overline{m} = \frac{m_o}{m_w};\ g = \bar{g}L\,\Delta\gamma\sin\theta;\ \bar{t} = \frac{\bar{g}m_w t}{\bar{f}L^2(1-\overline{m})};\ G = \frac{\bar{g}}{\Delta p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and x is the fraction of the length, L, of the stratum to which the interface has advanced at the time t, g is the acceleration of gravity, $\Delta\gamma$ is the difference in density between the oil and water, $\bar{f}$ is the displacement porosity, *i.e.*, the porosity times the increase in water saturation in the water invaded pay, and Δp is the driving pressure difference measured at the same datum level, and corrected for an oil gravity gradient. L represents the total distance along the stratum of interest. The integral of Equation (1) is:

$$\bar{t} = x + \left(\frac{1}{G} - \frac{1}{1-\overline{m}}\right)\log(1-Gx) \quad . \quad . \quad . \quad (3)$$

For the special case $G \sim 0$, where there is no gravity effect, Equation (3) reduces to:

$$\frac{m_w t\,\Delta p}{(1-\overline{m})\bar{f}L^2} = x\left[\frac{1}{1-\overline{m}} - \frac{x}{2}\right] \quad . \quad . \quad . \quad . \quad (4)$$

And when the mobilities ahead and behind the water-oil interface are the same ($\overline{m} = 1$), Equation (3) takes the simple form:

$$\frac{\bar{g}m_w t}{\bar{f}L^2} = -\log(1-Gx) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Examples of the time histories predicted by Equation (3) are plotted in Fig. 2 for $\overline{m} = 0.2$ and $\overline{m} = 2$ for various values of G. To make the time scales comparable for the two values of $\overline{m}$, the abscissa variable was chosen as $(1-\overline{m})\bar{t}$. The different values of G correspond to differences in the values of the driving head.

As is to be expected, the curves for $\overline{m} = 2$ require longer time periods for completion of the advance of the water through the oil column than those for $\overline{m} = 0.2$. This results from the increasing flow resistance of the column as the oil is replaced by the water when $\overline{m} > 1$. This increase becomes aggravated as the advance continues, leading to the convex upward character of the curves. The converse behavior occurs for $\overline{m} < 1$.

The shift of the curves to the right as G increases simply reflects the corresponding decrease in driving head. In the limit when G approaches unity, the time for complete invasion becomes infinite. In fact, if the driving head is not sufficient to support the total differential head $gL\,\Delta\gamma\sin\theta$, the interface will asymptotically come to rest at a value $x = 1/G = \Delta p/gL\,\Delta\gamma\sin\theta$, as follows from Equation (3) and as can be derived directly from equilibrium considerations.

EFFECT OF RATE ON INTERFACE HISTORY

Since the individual or absolute mobilities enter the above equations only in the dimensionless time $\bar{t}$, the basic functional history of advance of the water-oil interface, *i.e.*, Equation (3), will be independent of the permeability of the stratum. The latter will control only the time scale. On the other hand

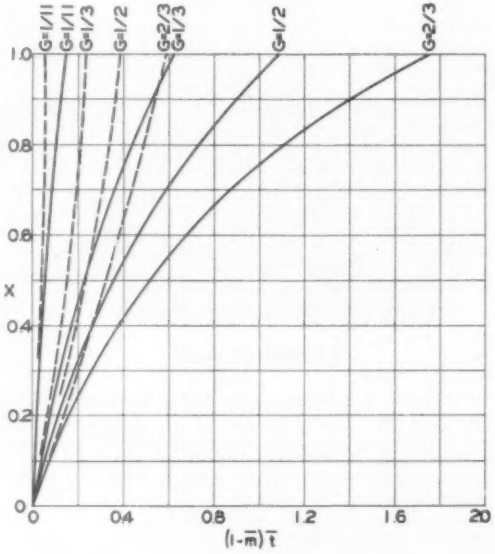

FIG. 2 — HISTORY OF UP-DIP WATER INVASION INTO UNIFORM OIL PRODUCTIVE FORMATIONS.

x = Fraction of total length of oil stratum invaded by water. $\overline{m}$ = (mobility of oil ahead of interface)/(mobility of water behind interface). $\bar{t}$ = Dimensionless time. G = Ratio of total differential fluid head of oil stratum to pressure differential at datum of original water-oil interface. Solid curves, $\overline{m} = 2$. Dashed curves, $\overline{m} = 0.2$.

since this functional history involves the rate sensitive term G representing the effect of gravity, the relative advance of the interface in zones of different permeability at any given time will also depend on the term G.

This rate sensitivity of the water invasion process may be evaluated by comparing the relative degrees of advance of the water in strata of different permeability as a function of the gravity parameter G. This could be done by reference to the time history curves such as are plotted in Fig. 2. A more direct procedure, however, is that of determining the extent of the advance of the water-oil interface in a stratum of relatively low permeability at the time when complete invasion has developed in an otherwise identical zone but having a higher absolute permeability. Denoting by R the ratio of the mobility of either fluid in stratum (2) to that in stratum (1), and assuming* all other characteristics to be identical, *i.e.*, on setting:

$$R = \frac{m_{w2}}{m_{w1}} = \frac{m_{o2}}{m_{o1}} \quad \ldots \ldots \ldots \quad (6)$$

it may be shown by application of Equation (3) that the fractional invasion in stratum (2) at the time stratum (1) has been completely flooded will be:

$$x_2 = R + \left(\frac{1}{1-\overline{m}} - \frac{1}{G}\right)[\log(1-Gx_2) - R\log(1-G)] \quad (7)$$

*It is further assumed that there is no cross flow between the layers of different permeability.

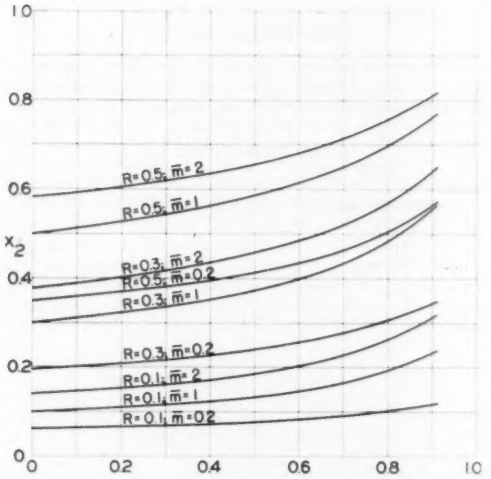

FIG. 3 — THE RELATIVE ADVANCE OF WATER-OIL INTERFACES IN TIGHT STRATA BY THE TIME INVASION HAS BEEN COMPLETED IN PERMEABLE STRATA.

x_2 = Fractional extent of invasion in tight stratum at time permeable zone is completely flooded. R = (Permeability of tight stratum)/(permeability of completely invaded stratum). $\overline{m}$ = (mobility of oil ahead of interface)/(mobility of water behind interface). G = Ratio of total differential fluid head of oil pay to pressure differential at datum of original water-oil interface.

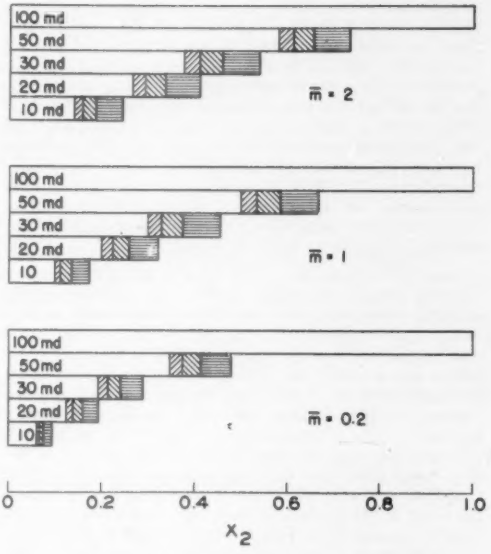

FIG. 4 — DIAGRAMATIC REPRESENTATION OF DEGREES OF ADVANCE OF WATER IN STRATA OF PERMEABILITIES 50, 30, 20, AND 10 MD, AT THE TIME A PARALLEL 100 MD STRATUM IS COMPLETELY FLOODED BY INVADING EDGEWATER.

$\overline{m}$ = (mobility of oil ahead of interface)/(mobility of water behind interface). x_2 = Fractional distance of advance of water-oil interface in tighter strata at the time the 100 md zone is completely flooded. G = Ratio of total differential fluid head of oil pay to driving pressure differential at datum of initial water-oil contact. 1st interface refers to $G = 0$; 2nd interface refers to $G = 0.25$; 3rd interface refers to $G = 0.50$; most advanced interface corresponds to $G = 0.75$.

For the special case $\overline{m} = 1$, Equation (7) reduces to:

$$x_2 = [1 - (1-G)^R]/G \quad \ldots \ldots \quad (8)$$

Several illustrative curves of x_2 *vs* G, as computed by Equations (7) and (8), are plotted in Fig. 3. The relative positions of the curves for the different values of R reflect the direct effect of the permeability on the rate of water invasion. In the limit $R = 1$, x_2 would equal 1 for all $\overline{m}$ and G, since the two strata (1) and (2) would then be identical. The ordinate intercepts for $G = 0$ give the advance in the tighter strata when the more permeable zone is completely flooded if gravity had no effect, *i.e.*, for horizontal beds or water and oil of equal density. These intercepts equal R when $\overline{m} = 1$, but differ from R when $\overline{m} \neq 1$, because of the changing fluid conductivity of the system as the water invasion progresses.*

The rising trend of the curves gives a direct measure of the rate sensitivity of the invasion process. This sensitivity does not vary greatly with $\overline{m}$ and R, but it does increase as G increases. And in the limit as $G \rightarrow 1$, x_2 in all cases approaches 1. This means that all zones will be flooded out at the same (infinite) time regardless of their permeability.

A somewhat more graphic representation of the effect of gravity in equalizing the differential water advance in strata of different permeability is shown in Fig. 4. Here are plotted

*This factor has been previously analyzed in detail for continuously stratified media (*cf.* M. Muskat, *Trans.* AIME, 1950, **189**, 349-358).

diagramatically the relative degrees of advance in a series of parallel strata of 10, 20, 30, 50 and 100 md permeability.* These correspond respectively to strata for which $R = 0.1$, 0.2, 0.3, 0.5, and 1.0. In this figure are shown the relative positions of the water-oil interface in the tighter strata at the time the 100 md zone is completely flooded out. The first interfaces give the positions if gravity were not acting on the system, or if the latter were horizontal ($G = 0$). The subsequent interfaces, separated by the hatched areas, denote the positions for values of $G = 0.25$, 0.50, and 0.75 respectively. Three such systems are illustrated, *i.e.*, those for which $\overline{m} = 0.2$, 1.0, and 2.0. The comparative features of these diagrams illustrate the same trends plotted in Fig. 3.

Aside from the validity of the simplifications introduced in carrying through the above analyses and calculations, the practical significance of the results depends on the range of values of G which may be expected to occur under actual field conditions. From the definition of G in Equation (2) it follows that its value will depend both on the fixed reservoir-fluid properties, $\Delta\gamma L \sin\theta$, and the pressure drop Δp supporting the water invasion, and which can be controlled, in principle, by the withdrawal rates. If we choose for the density difference $\Delta\gamma$, the value 0.3, and a dip angle θ of 10°, the vertical differential head for a surface distance of 1,000 ft will be equivalent to 23 psi. G will then be the ratio of this head to the pressure drop at the same datum over the 1,000 ft distance. From Figs. 3 and 4, it appears that substantial equalization in the water advance will not develop until G is about 0.8 or greater. This would correspond to a pressure drop of only about 30 psi in this particular case.

To see what this would imply in terms of field withdrawals, we may suppose the equivalent gradient of about 0.03 psi/ft is applied along the periphery of a circular field, one mile in radius (~2,000 acres area), the productive section being 25 ft thick and the average effective mobility being 25 md/cp. A corresponding initial and maximum rate of water influx would then be 675 B/D. If the field is operated by complete water drive, and is developed on a 40-acre spacing the withdrawal rate per well would have to be only 13.5 B/D in reservoir volume. Moreover, this will decrease as the water entry continues and the retarding head of the water column reduces the net driving force.

In this particular example an effective control of edgewater "fingering" of the type considered here by limiting the producing rate would hardly be practical. And it appears likely that in most actual producing operations in fields of moderate permeability, where an attempt is made to produce by the water drive mechanism the possibility of controlling the uniformity of advance of the edgewater by varying the withdrawal rates will be rather limited. On the other hand, in steeply dipping and highly permeable formations definite benefits may well result from withdrawal control. Thus, in the above example, if the effective fluid mobility be increased by a factor of 10, the initial rate of water influx could support a withdrawal rate of 135 B/D per well in reservoir volume, and yet have a value of $G = 0.8$.

Another situation where low gradients near the water-oil contact may be effective in equalizing the differential advance of the interface is that where the major producing mechanism is that of gravity drainage, supplemented by gas cap injection and expansion. If water invasion is not the primary agent for the mass oil migration, the low gradients near the interface will tend to make such intrusion as does take place more uniform than would occur under rapid water drive encroachment.

ACKNOWLEDGMENT

The writer is indebted to Miss M. O. Taylor, of the Gulf Research and Development Co., for carrying through the numerical calculations cited in this paper.

REFERENCES

1. Buckley, S. E., and Leverett, M. C.: "Mechanism of Fluid Displacement in Sands," *Trans.* AIME (1942) 146, 107. ★

*This treatment of a discreet layer system can be generalized to continuously stratified media. For the special case of a linear permeability distribution, it is found that the fraction of the total section which would be flooded by the time the water has just broken through the most permeable zone will be:

$$\text{Fraction flooded} = \frac{r}{(r-1)\,[1-\alpha'\log(1-G)]}\left[\frac{1-x_m^2}{2}-\alpha'(1-x_m)+\frac{\alpha'}{G}\log\frac{1-Gx_m}{1-G}\right]$$

where r is the ratio of maximum to minimum permeability, x_m is the fractional advance in the tightest layer, and $\alpha' = \frac{1}{1-\overline{m}}-\frac{1}{G}$, the rest of the notation being the same as in the text.

A RESERVOIR ANALYZER STUDY OF THE WOODBINE BASIN

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ABSTRACT

This paper presents a reservoir analyzer study of the performance of the Woodbine formation in the East Texas basin. The study was made possible by the compilation of available information on the configuration, thickness and the pressure drawdown of the formation. The investigation was made of the pressure variations in the basin incident to production from the several Woodbine reservoirs. In addition, the apparent compressibility of Woodbine water was evaluated so that the potential water yield of the formation could be determined. The distribution of permeability of the Woodbine sand and the interference between producing areas were also investigated. In conjunction with this basic study of the Woodbine sand, an acceptable match of the production-pressure relationship in the East Texas Field was established on the analyzer.

INTRODUCTION

When production is taken from a reservoir contiguous to an aquifer, the resultant pressure gradient causes a water influx into the reservoir. For some years it has been the practice to predict the performance of water drive reservoirs with mathematical equations that relate the water influx into reservoirs to their pressure behavior. A rigorous solution of these equations is quite complex; hence, the conventional method requires the simplifying assumptions that the formation have constant thickness, permeability and porosity, and that it have a known and regular shape. It is necessary to use performance records of the reservoir in question to determine the equation constants that make the results of the mathematical calculations duplicate the reservoir history. The values of the constants determined in this manner sometimes differ so greatly from theoretical or measured values that the constants appear unreasonable. The equation constants comprise such factors as the thickness, porosity and permeability of the formation, and the viscosity and compressibility of water. Usually the thickness, porosity and viscosity are known within a reasonable degree of certainty, whereas the formation permeability and the water compressibility are known with considerably less certainty. Hence, permeability and compressibility values are arbitrarily selected that will make the mathematical equations duplicate the reservoir behavior. In many reservoir studies the value of the compressibility of water thus selected has exceeded the reported value by a factor of from severalfold to manyfold. Whether this excessive value results from the inadequacy of the mathematical approach to take into account the shape irregularities and the heterogeneities of the aquifer, or is due to some type of formation compaction and decrease of porosity has not been established. Because of the significance of the potential water yield of formations with reference not only to oil reservoirs but to water resources as well, it is very important that a representative value for the effective water compressibility be determined.

One of the best known examples of a field for which it has been possible in the past to predict the future reservoir pressure is the East Texas Field. Until about 1943 it was possible by means of mathematical equations to duplicate past pressure behavior and to predict with a high degree of accuracy the reservoir pressure of the field. Since 1943, however, the calculated pressures have deviated progressively from the observed pressures to such a degree that in recent years, it has

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch August 28, 1951. Paper presented at the Petroleum Branch Fall Meeting in Oklahoma City, Oct. 3-5, 1951.

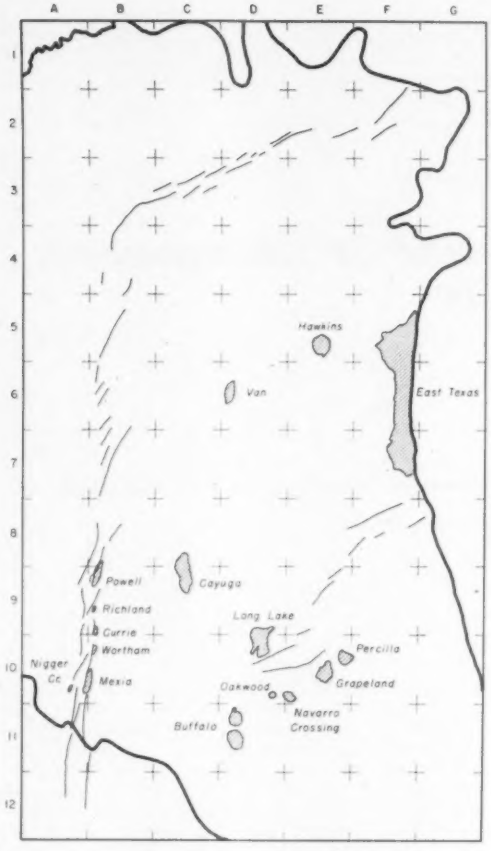

FIG. 1 — SUBDIVISION OF WOODBINE BASIN.

not been possible to predict accurately the future pressure of the field using the equation constants that were employed in the past. The geometric configuration and the permeability variation of the Woodbine aquifer, which is the source of the water drive for the field, and the production from other Woodbine fields were thought to be causing the discrepancy between the observed and calculated pressures.

As an approach to these problems, a detailed study of the Woodbine basin was made with an electric reservoir analyzer to determine the apparent compressibility of the formation water and the permeability variation throughout the basin, and to obtain a reliable means of predicting the pressure of the East Texas Field. In this study the aquifer was represented by an electric analogy in which variations in the geometry and the permeability of the sand were included. The apparent water compressibility and the permeability variations were determined from the analyzer constants and network condenser and resistor values that gave a basin pressure distribution consistent with the observed pressure history of the East Texas Field and the known pressure drawdown in the basin as of Jan. 1, 1947. The pressure pattern throughout the basin during the entire history of production from the Woodbine formation was derived simultaneously with this study.

In addition, the study provided a satisfactory means of determining the pressure history of the East Texas Field. From the electric characteristics of the analog, the influence of production from other fields on the pressure of the East Texas Field was determined, and predictions of the future pressure-production behavior of this field were made.

Insofar as is known by the authors, the Woodbine basin is the only producing formation about which sufficient data have been compiled to permit a quantitative study of an entire aquifer. Basic information available for this study included Woodbine formation pressures derived both from field measurements and from drill stem tests throughout the basin. The configuration of the Woodbine formation and the distribution of the net sand thickness were also known.

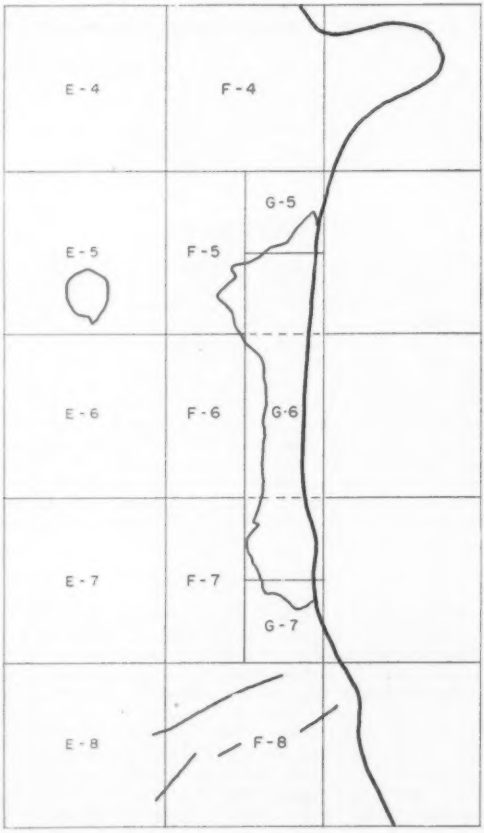

FIG. 2 — SUBDIVISION OF AREA AROUND EAST TEXAS FIELD.

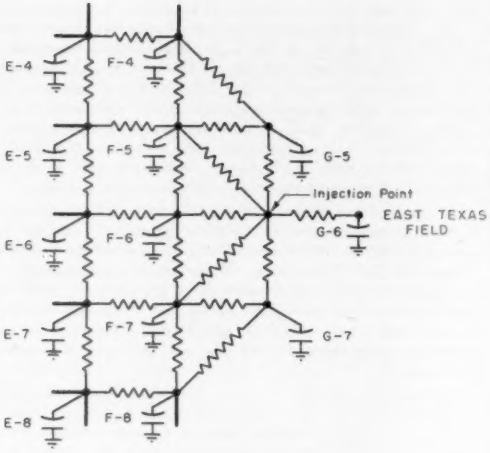

FIG. 3 — RESISTOR NETWORK.

STUDY OF THE BASIN

Electric Representation of the Woodbine Basin

To represent the Woodbine basin electrically on the pool unit of the reservoir analyzer, the area of the basin was divided into a number of squares 15.42 miles on the side as shown by the grid map on Fig. 1. On this map are shown the location of the Woodbine reservoirs that were considered in this study. The three squares enclosing the East Texas Field were subdivided further as shown on Fig. 2 so that the subdivision in which the field lay approximated closely the areal extent of the field. For each of the integral formation volumes corresponding to these area subdivisions, the fluid capacitance, which is defined as the product of the interstitial fluid volume and the appropriate fluid compressibility, was represented by an electric condenser. The equation for arriving at the relative condenser values is shown below:

$$C_E = M\, c\, ab\, \phi \qquad \ldots\ldots\ldots\ldots \quad (1)$$

where,

C_E = electric capacity of condenser, microfarads

M = analyzer proportionality constant between fluid and electric units, $\frac{\text{microfarads}}{\text{bbl/psi}}$

c = compressibility of interstitial fluid, vol/vol/psi

ab = volume of formation sand within each square, bbl

ϕ = porosity of sand, fraction of total sand volume

The compressibility of the water and the porosity of the sand were assumed to be constant everywhere in the aquifer, whereas the sand volume corresponding to each areal subdivision was determined from the average clean sand thickness for each subdivision as indicated by electric logs of the wells drilled throughout the basin.

The condensers representing the fluid capacitance of the Woodbine formation were arranged in the same pattern as the corresponding areas. The resistance to fluid flow between the centers of adjacent formation subdivisions was represented by a variable resistor, so that for each boundary common to two areal units there was a resistor connecting the corresponding condensers. The resistors representing paths of flow from the aquifer across the East Texas Field boundary were tied together to form a common point to which was attached a single resistor terminated by the condenser representing the East Texas Field. Each resistor bears the inverse relationship to the corresponding formation permeability shown by the following equation:

$$R_E = \frac{N\,\mu}{0.001127\,K\,b} \qquad \ldots\ldots\ldots \quad (2)$$

where,

R_E = electric resistance, megohms

N = analyzer constant, $\frac{\text{megohms}}{\frac{\text{psi}}{\text{B/D}}}$

μ = viscosity of Woodbine water, centipoises

0.001127 = proportionality constant to change millidarcys to $\frac{\text{(bbl)\ (sq in.)\ (cps)}}{\text{(lb)\ (day)\ (ft)}}$

K = permeability, md

b = clean sand thickness on side of formation subdivision, ft

In order to simulate production from the fields producing from the Woodbine sand, current was withdrawn from the charged resistor-condensor network at the appropriate mesh points. To simulate injection of water along the western edge of the East Texas Field, current proportional to the volume of water injected into the field was introduced at the junction of the resistor leading to the field and the resistors leading to the aquifer as is shown on Fig. 3.

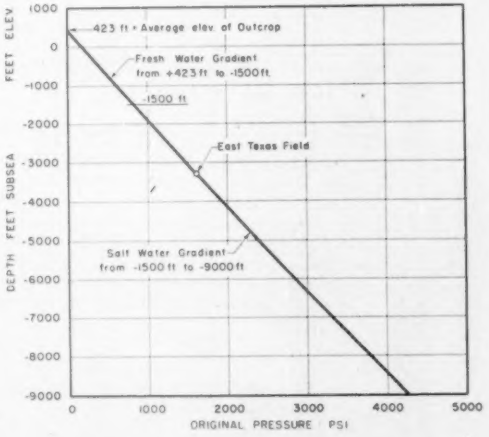

FIG. 4 — WOODBINE BASIN — PRESSURE VS DEPTH.

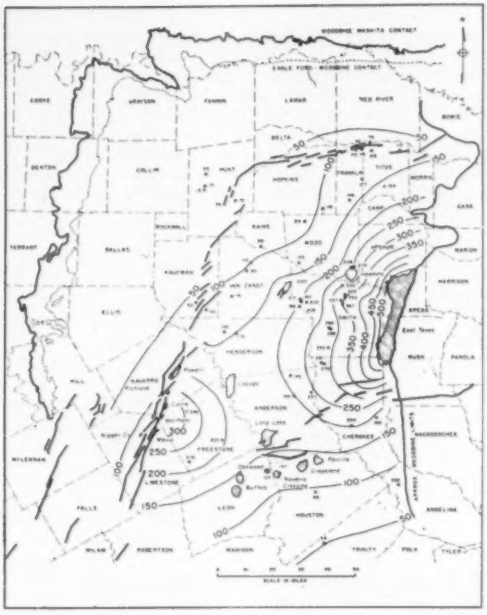

FIG. 5 — PRESSURE LOSS IN WOODBINE BASIN ON JAN. 1, 1947.

Pressure Loss in the Basin

During the last decade, drill stem tests were made on many of the wells drilled into the Woodbine formation. In conjunction with these tests, pressures were measured in the Woodbine formation, and water samples were taken.[1] From the density and chloride content of these samples, and the depths at which they were taken, the relationship between original pressure in the Woodbine sand and subsea depth was established. This relationship is shown on Fig. 4. By means of this relationship and the measured pressures, the change from original pressure was determined for each of the different well locations as of the date on which the pressure measurement was made. A preliminary analyzer study of these pressure changes provided an indication of the approximate rates of change in pressure in the various parts of the basin. These were used to adjust observed pressures to an arbitrary date of Jan. 1, 1947.

In an analyzer study of the performance of a reservoir, a charged condenser of an arbitrary capacity is used to express the product of the volume of a compressed fluid and its compressibility. The original voltage across the condenser is analogous to the original formation pressure. In such an analogy the drop in voltage across the condenser remains proportional to the volume-weighted pressure decline in the formation. Therefore, volume-weighted pressures were used in this study.

The pressure drawdown of the Woodbine basin, contoured at 50 psi intervals by the use of adjusted pressure losses, is shown on Fig. 5. Volume weighted pressure losses for the squares into which the basin had been sub-divided were determined from this map of pressure drawdown in the basin in conjunction with an isopach map of the clean sand thickness in the basin and are presented on Fig. 6.

Match of Pressure Loss in the Basin

The reservoirs that had produced or were producing from the Woodbine formation were surveyed to determine which of them had production of sufficient magnitude to cause water efflux from the basin into the reservoirs in such quantities as to affect appreciably the pressure pattern of the basin. The water efflux from the basin was expressed in terms of the rates of water influx into the various reservoirs considered. The water influx rates of each of these reservoirs were calculated for their producing histories where the necessary data existed and were carefully estimated for the fault line fields where water production data were not available. The effects

Table I — Daily Average Water Influx Rates

						Production Controller No. 6 Sq.: E-10					Production Controller No. 7 Sq.: B-9				Production Controller No. 8 Sq.: B-10			
Year	Prod. Contr. No. 1 Sq.: F-5a* East Texas B/D	Prod. Contr. No. 2 Sq.: E-5 East and West Hawkins B/D	Prod. Contr. No. 3 Sq.: D-6 Van B/D	Prod. Contr. No. 4 Sq.: C-9 Cayuga B/D	Prod. Contr. No. 5 Sq.: D-10 Long Lake B/D	Navarro Crossing B/D	Buffalo B/D	Grapeland B/D	Percilla B/D	Group Total B/D	Powell B/D	Richland B/D	Currie B/D	Group Total B/D	Wortham B/D	Nigger Creek B/D	Mexia B/D	Group Total B/D
1921																	17,000	17,000
1922													7,000	7,000			137,000	137,000
1923											103,000		9,000	112,000			103,000	103,000
1924											189,000	17,000	8,000	214,000			81,000	81,000
1925											142,000	25,000	5,000	172,000	11,000		67,000	78,000
1926											119,000	22,000	4,000	145,000	57,000	8,000	64,000	129,000
1927											112,000	23,000	4,000	139,000	39,000	35,000	64,000	138,000
1928											98,000	25,000	4,000	127,000	31,000	22,000	57,000	110,000
1929											95,000	24,000	5,000	124,000	24,000	15,000	53,000	92,000
1930			13,000								93,000	18,000	4,000	115,000	19,000	10,000	48,000	77,000
1931	379,000		39,000								76,000	7,000	4,000	87,000	9,000	4,000	43,000	56,000
1932	504,000		56,000								63,000	4,000	3,000	70,000	4,000		36,000	40,000
1933	725,000		53,000								77,000	4,000	3,000	84,000	3,000		36,000	39,000
1934	646,000		14,000								71,000	4,000	3,000	78,000	3,000		36,000	39,000
1935	621,000		76,000								72,000	3,000	3,000	78,000	3,000		40,000	43,000
1936	603,000		25,000								75,000	2,000	3,000	80,000	2,000		40,000	42,000
1937	666,000		33,000		12,000			1,000		1,000	82,000	1,000	4,000	87,000	2,000		40,000	42,000
1938	629,000		11,000		34,000		2,000	—		2,000	78,000	2,000	3,000	83,000	2,000		39,000	41,000
1939	637,000		15,000		27,000		2,000	—		2,000	74,000	2,000	4,000	80,000	2,000		38,000	40,000
1940	624,000		12,000		16,000	8,020	1,000	4,000		13,000	71,000	2,000	4,000	77,000	4,000		36,000	40,000
1941	724,000		11,000		11,000	—	—	14,000		14,000	69,000	4,000	4,000	77,000	13,000		38,000	51,000
1942	697,000		2,000	4,000	28,000	6,000	—	14,000		20,000	62,000	3,000	5,000	70,000	13,000		40,000	53,000
1943	609,000		—	42,000	54,000	1,500	3,000	17,000		21,000	54,000	2,000	6,000	62,000	11,000		37,000	48,000
1944	539,000		11,000	70,000	48,000	—	1,000	33,000		34,000	54,000	2,000	5,000	61,000	8,000		37,000	45,000
1945	545,000	7,000	23,000	124,000	61,000	4,000	3,000	22,000		29,000	49,000	2,000	5,000	56,000	7,000		36,000	43,000
1946	489,000	13,000	21,000	134,000	46,000	6,000	2,000	24,000	1,000	33,000	60,000	3,000	5,000	68,000	6,000		36,000	42,000
1947	467,000	13,000	19,000	70,000	60,000	9,000	12,000	21,000	1,000	43,000	60,000	3,000	5,000	68,000	6,000		36,000	42,000
1948	443,000	15,000	32,000	69,000	82,000	7,000	8,000	18,000	3,000	36,000	60,000	3,000	5,000	68,000	6,000	•	32,000	38,000
1949	368,000	16,000	33,000	55,000	73,000	5,000	2,000	14,000	2,000	23,000	64,000	3,000	4,000	71,000	7,000		28,000	35,000
1950	372,000	14,000	25,000	52,000	63,000	8,000	2,000	3,000	2,000	15,000	63,000	3,000	4,000	70,000	6,000		28,000	34,000

*Note: The squares in which East Texas Field lay were subdivided into smaller divisions so that one condenser represented just the fluid capacitance of East Texas Field.

of production from the various reservoirs were reproduced on the analyzer by the withdrawal of currents proportional to the rates of water influx from the condensers corresponding to the areas in which the reservoirs lay. Since the analyzer used in this study has only eight current controller units, some of the reservoirs were grouped together. The water influx rates, reservoir groups, and squares from which current withdrawals were made are presented in Table I.

By a trial-and-error procedure of adjusting the resistor values representing the resistance to flow and the magnitude of the currents proportional to the water influx rates, the change in voltage across the condenser representing each square was made proportional to the volume-weighted pressure drop calculated for the square as of Jan. 1, 1947. In order to obtain a more nearly unique match of the whole basin, the voltage decline of the condenser representing the East Texas Field was made to simulate the volume weighted pressure decline of the field. The resultant voltage declines of the two condensers representing the Van Field and the Oakwood Field

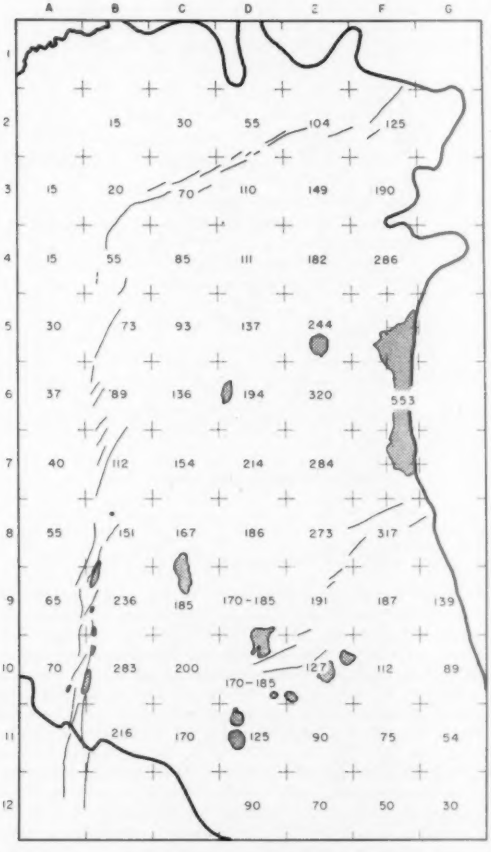

FIG. 6 — VOLUME-WEIGHTED PRESSURE LOSS AS OF JAN. 1, 1947 — OBSERVED.

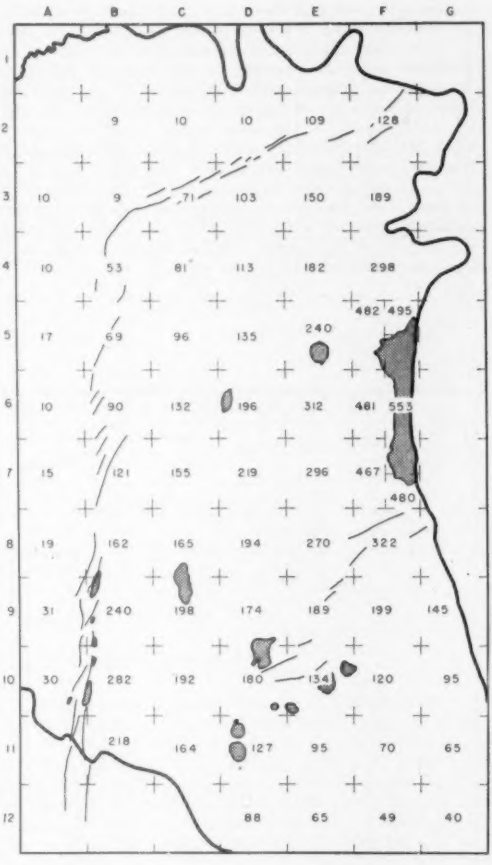

FIG. 7 — PRESSURE LOSS AS OF JAN. 7, 1947 — ANALYZER.

were then found to be reasonably consistent with the observed pressure declines in the two fields. Since these two comparisons appeared reasonable, it was felt that a fairly accurate solution of the pressure distribution had been obtained. Fig. 7 shows the distribution of the pressure drawdown in the basin as of Jan. 1, 1947, obtained with the analyzer. The agreement of these pressure changes with those shown on Fig. 6 is indicative of the accuracy of the analogy used.

Compressibility of Water

The proportionality constants, or analyzer constants, between fluid units and electrical units determined from the study of the basin distribution of pressure are presented in Table II. One of these constants, "M," which was found to

be 3.28×10^{-6} microfarads/bbl/psi, was used in Equation (1) with the values of the condensers representing the basin to compute the apparent compressibility of the water in the Woodbine basin. The porosity of this formation throughout the basin was assumed to be constant at 25 per cent. This computed value for the apparent compressibility, 5.3×10^{-6} vol/vol/lb/sq ft, is somewhat higher than the value of 1.85×10^{-6} vol/vol/lb/sq ft that was measured on samples of Woodbine water taken during drill stem tests. A study of the production-pressure relationship in the East Texas Field reported in the literature in 1938 indicated an apparent compressibility of 1.11×10^{-5} vol/vol/lb/sq ft for Woodbine water.[3] Earlier investigators reported values as high as 12 times the compressibility of pure water.[3,4]

FIG. 8 — PRESSURE LOSS — JAN. 1, 1930.

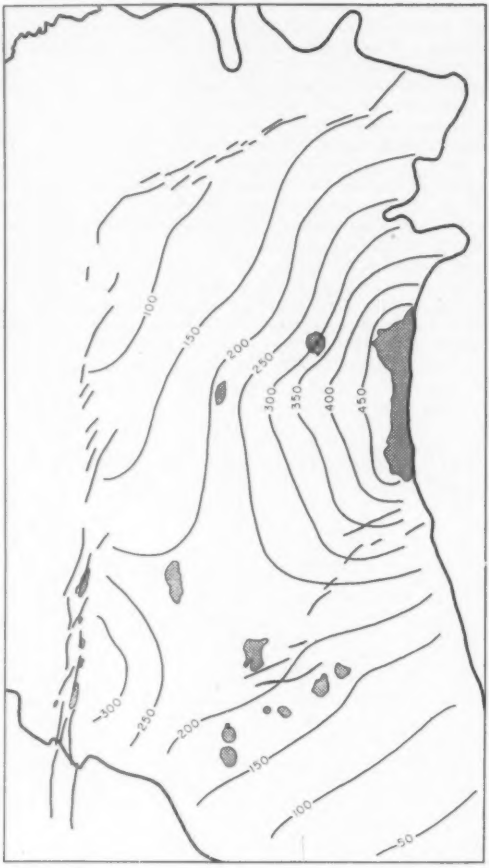

FIG. 9 — PRESSURE LOSS — JAN. 1, 1950.

A Bureau of Mines publication on the compressibility of consolidated sandstones presented information from which the effect of pressure on the pore volume could be computed.[5] The measured effect of pressure loss on Woodbine sand was to reduce the size of the pore volume by an amount equal to 2.85×10^{-6} vol/vol/lb/sq ft. On the assumption that this effect would be additive with the compressibility of the Woodbine water, the effective compressibility in the Woodbine aquifer would be 4.7×10^{-6} vol/vol/lb/sq ft. The agreement between this value and that experimentally determined with the analyzer is rather close and is well within the over-all accuracy of the analyzer study. However, the difference between the two might be accounted for by some other phenomenon which would result in a reduction of the volume of the pore space or by the intrusion of extraneous water into the Woodbine formation.

Table II — Analyzer Constants

Constant	Units	Pool Unit	Water-Drive Unit
L	volts/psi	0.300	0.3261
L/N	microamps / B/D	1.44×10^{-4}	1.246×10^{-4}
MN	sec/D	6.849×10^{-3}	3.219×10^{-2}
N	megohms / psi/B/D	2088	2617
M	microfarads / B/psi	3.28×10^{-6}	3.141×10^{-5}

As in independent approach, the apparent compressibility of Woodbine water was determined from the ratio of cumulative water yielded by the formation to the integrated product of the volume of Woodbine water and its observed loss in pressure to Jan. 1, 1947. For this purpose the water yielded was considered to be the sum of the volume of water influx into all fields producing from the Woodbine formation. This procedure gave a value of 5.6×10^{-6} vol/vol/lb/sq ft. The difference between this value and that obtained with the analyzer indicates the accuracy with which the basin pressure behavior was simulated on the analyzer.

Permeability Distribution

From another analyzer constant, "N," which was found to be 2,088 megohms/psi/B/D, Equation (2), and the values of the various resistors, the effective permeabilities at various locations in the basin were determined. In general, the permeability was found to be in the range of 1,000 to 1,500 md around the East Texas Field and to decrease to values from 100 to 700 md as the Mexia-Talco fault line is approached. Continuity across the fault block appeared to be very limited.

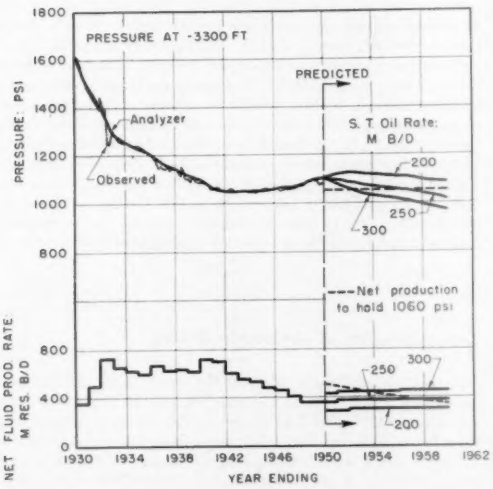

FIG. 10 — POOL UNIT REPRESENTATION, EAST TEXAS FIELD.

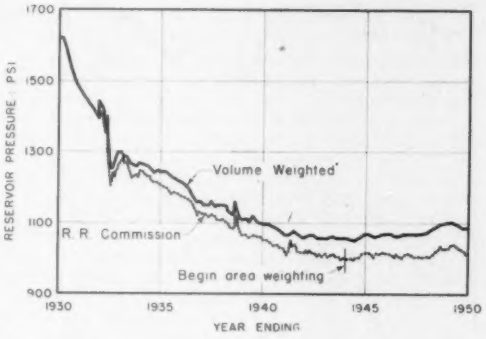

FIG. 11 — COMPARISON OF VOLUME-WEIGHTED AND AREA-WEIGHTED PRESSURES, EAST TEXAS FIELD.

Basin Pressure Behavior

The analyzer study indicated the manner in which the pressure drawdown throughout the basin has developed since production of the Woodbine field began. Figs. 8 and 9 show the pressure drawdown of the basin in 1930 and 1950. Major production from the basin began in 1921 with production from the Mexia-Powell fault-line fields, and by 1930 a pressure sink of some 400 psi was established around the Mexia-Powell area with a perceptible drawdown occurring as far east and north as 60 to 70 miles. The East Texas Field was discovered and began producing from the east edge of the basin late in 1930. Between this date and 1950 the production from the fault line fields declined, and the production from the East Texas Field became the dominant influence on the pressure of the basin. By 1950 marked interference existed between these two producing areas as is evident by the distortion of the pressure distribution about them, and their effects caused a pressure drawdown in all of the basin east and south of the Mexia-Talco fault.

STUDY OF THE EAST TEXAS FIELD

Pressure Predictions with the Pool Unit

One of the major controls in obtaining a match of the pressure distribution of the Woodbine basin on the reservoir analyzer was the duplication by the analyzer of the pressure history of the East Texas Field. This match of the pressure-production history of East Texas with the pool unit is shown on Fig. 10. The observed pressures in this illustration are the average pressures obtained by volume weighting. This

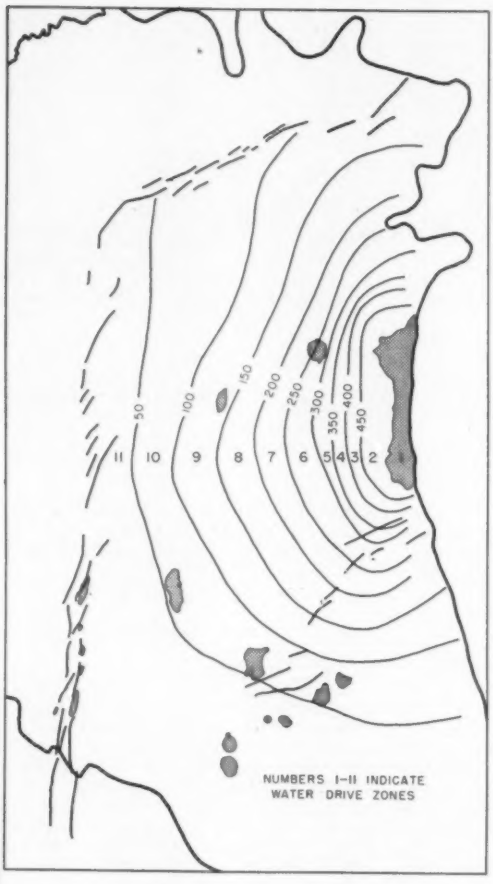

FIG. 12 — PRESSURE DRAWDOWN OF WOODBINE BASIN DUE TO EAST TEXAS FIELD PRODUCTION.

method of obtaining an average pressure for the field was used in place of the customary procedure of area-weighting, since the pressure obtained from the analyzer is a volume-weighted pressure. A comparison of the pressures derived from the two methods of averaging is presented on Fig. 11.

The pool unit representation of the East Texas Field was used to make predictions of the pressure in the field for the period Jan. 1, 1951, to Jan. 1, 1961, using oil production rates of 200,000, 250,000, and 300,000 bbl of stock-tank oil per day. The estimates of water production presented in Table III were based on the following assumptions:

1. The number of marginal wells will remain constant.
2. The rate of oil production from the marginal wells will remain at 20,419 bbl of stock-tank oil per day, the rate existing on Jan. 1, 1950.
3. The other wells will produce at a rate of 20 bbl of stock-tank oil per producing day.
4. Ninety per cent of the produced water will be returned to the Woodbine formation.
5. The rate of fluid production from the other fields producing from the Woodbine will be maintained at their 1950 rates.

Fig. 10 shows the predicted pressure behavior of the East Texas Field for the above rates of oil production. The 200,000 bbl of stock-tank oil per day rate resulted in a pressure rise from 1,100 to 1,130 psi by 1953, followed by a gradual decline to 1,095 psi by Jan. 1, 1961. The 250,000 bbl of stock-tank oil per day and the 300,000 bbl of stock-tank oil per day rates caused the reservoir pressure to decline over the 10-year period to 1,060 and 970 psi, respectively.

In addition to these predictions, the rate of net reservoir withdrawal that would be required to hold the volume-weighted pressure constant at 1,060 psi was determined for the period 1951 to 1961. A volume-weighted pressure of 1,060 psi during this period corresponds to an area-weighted pressure of approximately 990 psi. This rate was found to decrease gradually from the initial net fluid withdrawal rate of 500,000 reservoir B/D to 360,000 reservoir B/D. These rates are equivalent to 320,000 and 230,000 bbl of stock-tank oil per day, respectively. This study indicated that, even though the basin is considerable in expanse, the portion readily available for the water drive under which the East Texas Field is producing is bounded on the north and west by the Mexia-Talco fault, across which there is limited continuity. This should have a significant effect on future field behavior, and should necessitate the return to the formation of nearly all produced water and a gradual decrease in production rate to maintain an area-weighted pressure of 990 psi.

Table III — Estimates of Water Production

Oil Rate		Water Rates	
S.T. B/D	Date	Production B/D	Injection B/D
200,000	1-1-51 to 9-1-52	502,200	452,000
	9-1-52 to 9-1-59	637,400	573,700
	9-1-59 to 1-1-61	688,100	619,300
250,000	1-1-51 to 4-1-52	532,300	479,000
	4-1-52 to 10-1-57	707,600	636,800
	10-1-57 to 1-1-61	769,000	692,100
300,000	1-1-51 to 1-1-52	563,100	506,760
	1-1-52 to 7-1-56	777,700	700,000
	7-1-56 to 1-1-61	851,750	766,600

Determination of Available Water

In order to determine whether the water yield will be sufficient from the Woodbine basin to produce by water drive the two and a half billion bbl of recoverable oil remaining in the East Texas field, the effects of maintaining the pressure at two different levels were investigated by means of the pool unit representation of the basin. It was determined that if the volume-weighted pressure in the reservoir is maintained at 1,020 psi, six billion bbl of water will enter the East

Table IV — Average Permeability in the Water-Drive Zones

Zone	Permeability millidarcys	Zone	Permeability millidarcys
1-2	1,644	6-7	723
2-3	1,866	7-8	699
3-4	755	8-9	722
4-5	761	9-10	351
5-6	655	10-11	294

Texas reservoir from the Woodbine basin. Similarly, if the reservoir pressure is maintained at 820 psi, ten billion bbl of Woodbine water will enter the reservoir. Hence, it appears that there will be more than sufficient water yield from the Woodbine aquifer to produce by water drive the remaining two and a half billion bbl of stock-tank oil from the East Texas Field if the present practice of returning 90 per cent or more of the produced water to the Woodbine formation is continued.

Representation on the Water-Drive Unit

The detailed variations in reservoir pressure caused by abrupt changes in the production rate were not duplicated on the pool unit of the analyzer, since the field was assumed to have an average rate of withdrawal for each year. To match the month-to-month fluctuations in pressure, it was desirable that the water-drive unit be employed because the greater number of time periods available on that unit permitted a breakdown of the production history into smaller increments. To transfer the problem from the pool unit to the water-drive unit, it was desirable to determine the pressure distribution in the Woodbine basin due to production from the East Texas Field alone. With the same pool-unit network used to obtain the match of the volume-weighted pressure decline of the East Texas Field, the basin pressure drawdown due solely to the production from the East Texas Field was determined as of Jan. 1, 1947, and is shown on Fig. 12.

In the transfer of the problem from the pool unit to the water-drive unit of the analyzer, the Woodbine aquifer was divided into 11 approximately semi-circular, concentric zones about the East Texas Field with zone boundaries corresponding to the pressure contours shown on Fig. 12. Each of these zones was represented by an electrical capacitance, the value of which was computed from the water compressibility determined on the pool unit to be 5.3×10^{-6} vol/vol/lb/sq ft and from data regarding the size and thickness of the aquifer.

Table V — Water-Drive Resistor and Condenser Values

Zones	Resistor megohms	Condenser microfarads
1	0.280	8
2	.200	10
3	.200	15
4	.300	19
5	.200	15
6	.300	45
7	.300	81
8	.300	103
9	.800	155
10	1.600	250
11	off	310

To arrive at apparent permeabilities for each of the zones, the zone boundaries were superimposed on a map showing the apparent permeabilities that were obtained from the pool unit. An average value was then estimated for the permeability between adjacent concentric zones. These values are presented in Table IV and were used in calculating the values of the water-drive resistors. The representation of the East Texas Field and its aquifer on the water-drive unit, then, was consistent with the pool-unit representation insofar as compressibility of the Woodbine water and the apparent permeability distribution of the aquifer were concerned. The constants for both the pool-unit and water-drive unit studies are presented in Table II. Table V presents the values of the water-drive resistors and condensers.

In an ideal aquifer for any finite time, the pressure drawdown at a point a given distance from a production point is theoretically a linear function of the rate of production. This fact, in conjunction with the principle of superposition, indicates that the pressure drawdown resulting from production a given distance away is always independent of the number of production points. This would indicate that the effect of any basin production on the pressure in the East Texas Field might be closely approximated in the water-drive unit study by the withdrawal of a proportional current from the zone condenser corresponding to the area in which the point of production lay.

A satisfactory match of the volume-weighted pressure behavior of the East Texas Field was obtained on the analyzer by the withdrawal of appropriate production from the zones in which producing fields lay. This match is shown on Fig. 13. As a further check on the validity of this method of representing the problem, predictions of the pressure behavior of the East Texas Field were made at the same rates of produc-

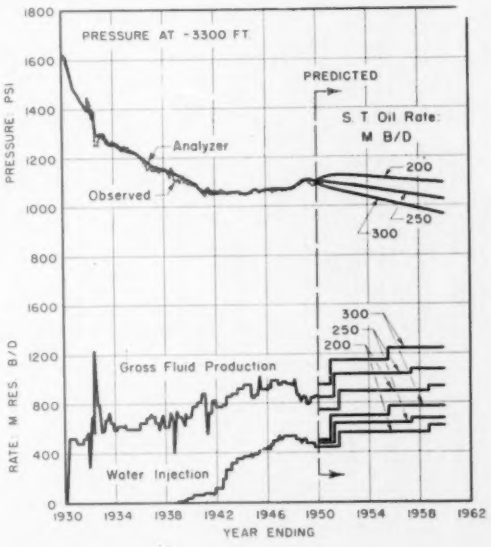

FIG. 13 — WATER DRIVE UNIT REPRESENTATION, EAST TEXAS FIELD.

tion as were used in the pool-unit study. The predictions with the water-drive unit are presented on Fig. 13. These predictions check closely with those obtained in the pool-unit study. The close agreement between the two methods indicates that even though there is interference between fields, reservoir studies can be made of those fields with the water-drive unit.

CONCLUSIONS

The analyzer study of the Woodbine basin indicates that the value of the effective compressibility of water used in conventional mathematical reservoir studies should be higher than that of the water alone. The agreement between the value, 5.3×10^{-6} vol/vol/lb/sq ft, obtained for the apparent compressibility of the Woodbine water and the sum, 4.7×10^{-6} vol vol/lb/sq ft, of the measured compressibilities of the water and sand indicates that these may be the major components of the apparent compressibility.

The study indicated that the apparent permeability of the Woodbine sand is 1,000 to 1,500 md in the vicinity of the East Texas Field, and decreases to 100 to 700 md near the Mexia-Talco fault line. The data on the pressure drawdown west of the Mexia-Talco fault line were too meager to determine accurately the long range effect of the fault on the pressure distribution in the Woodbine basin; however, there appears to be little effective communication across the fault line.

The presentation of the Woodbine basin on the analyzer provides a satisfactory match of the pressure performance in the East Texas Field, and should therefore furnish a convenient means of predicting future pressures. However, the pressure behavior of the field should still be predictable with the use of the mathematical equations if the proper boundary conditions are applied. The magnitude of the effects of the Mexia-Talco fault line and the production from other fields on the pressure of the East Texas Field are of sufficient magnitude that they must now be accounted for in any computation of the performance of the field. This study of the performance of the East Texas Field and of the associated Woodbine aquifer on the reservoir analyzer indicated that if the present practice of returning 90 per cent or more of the produced water to the Woodbine formation is continued, an area-weighted pressure of 990 psi can be maintained provided there is also a gradual decrease in the rate of production. The study further indicated that with the current practice of return of produced water, there will be sufficient water yield from the aquifer to produce the East Texas Field to depletion under the water-drive mechanism.

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POROSITY-MEASUREMENT COMPARISONS BY FIVE LABORATORIES

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ABSTRACT

A core sample porosity-check program is described. A number of laboratories participated in the investigation, which comprised measuring the porosities of ten selected natural and synthetic core samples. Each laboratory employed its own method (or methods) of measurement. These included Boyle's Law, water-saturation, and organic liquid-saturation methods. Brief descriptions of each method employed are given. In general, the measured values of porosity were in reasonably good agreement. The average deviation of porosity from the mean or average values for the group of samples was ±0.5 porosity per cent. The results of these measurements are compiled and presented in graphical form.

INTRODUCTION

The total bulk volume of a porous sample is derived from the sum of two volumes, the void or pore volume and the solid* or grain volume. The porosity fraction of the sample is defined as the ratio of the void volume to the bulk volume. Multiplication of this ratio by 100 converts it to per cent porosity.

Distinction is made here between total porosity and effective porosity. The former includes all void space, both interconnected and isolated, while the latter includes only those voids which are interconnected. This investigation deals only with the effective porosity.*

Numerous cases had been noticed in which there appeared to be appreciable discrepancies in the results of porosity determinations on core samples. Differences of as much as 10 to 15 porosity per cent had been reported from different sources

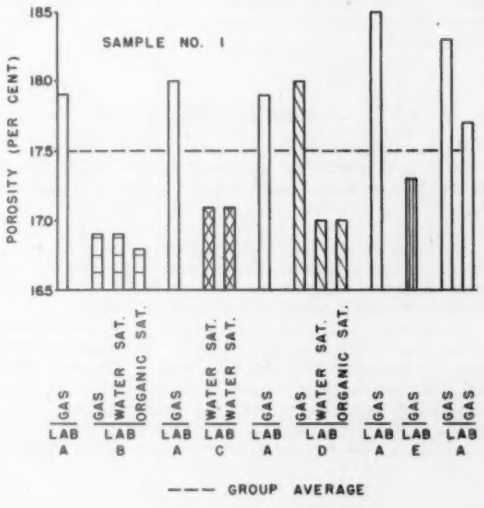

FIG. 1 — CORE SAMPLE POROSITY.

Manuscript received in the office of the Petroleum Branch Aug. 8, 1951.

*In this paper, the term "solid volume" includes all entrapped or non-interconnected void space.

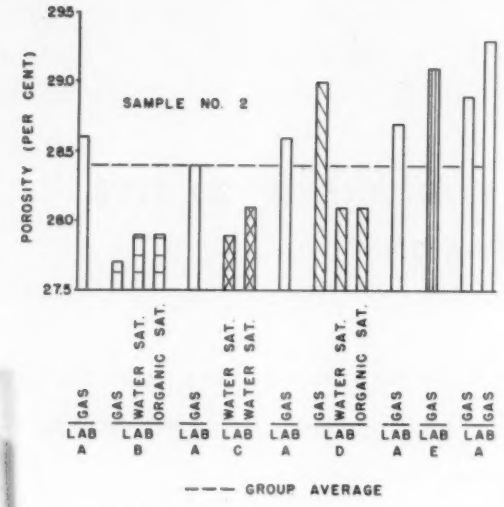

FIG. 2 — CORE SAMPLE POROSITY.

Table I — Characteristics of Samples Used in the Porosity-Check Program

Sample Number	Type	Sample Supplied By	Approximate Gas Permeability (md)	Approximate Porosity (%)
1	Limestone	Atlantic	1	15
2	Fritted Glass	Magnolia	2	35
3	Sandstone	Magnolia	20	15
4	Sandstone	Magnolia	1,000	20
BZE	Semi-quartzitic sandstone	Atlantic	0.2	4
BZG	Semi-quartzitic sandstone	Atlantic	0.8	4
61-A	Alundum	Magnolia	1,000	26
722	Alundum	Atlantic	3	17
1123	Chalk	Magnolia	1.6	33
1141-A	Sandstone	Magnolia	45	20

for the same sample. It was believed that the petroleum industry would be desirous of knowing the order of reproducibility of results that would be obtained, under controlled conditions, where different current methods of measurement were employed, or where different operators of the same method were involved.

A number of laboratories* agreed in November, 1949, to lend their efforts to such an investigation and to submit the information obtained for publication. Each laboratory was to employ its own method (or methods) for measurement, and preferably make these measurements under normal routine conditions.

PROCEDURE

Ten core samples which were quite varied in their characteristics were selected for the porosity-check program (See Table I). Both natural and synthetic samples with varying degrees of consolidation were included in this set of core samples.

The size of the samples was limited to three-fourths to seven-eighths inches in diameter by three-fourths to seven-eighths inches in length, to insure that all could easily be accommodated in the various pieces of measuring equipment.

The following procedure was agreed to by all participants in the program. The porosity values were first determined by Magnolia Petroleum Co.'s Field Research Laboratories, after which the samples were shipped to another one of the participating laboratories, together with a printed form data sheet. The samples, as shipped, were ready for porosity determinations, except for any extra drying procedure deemed advisable by each laboratory. Upon completion of the measurements by each recipient, the samples, together with the completed data form, were returned to the Field Research Laboratories for re-measurement. This process was then repeated until measurements had been made by all participants. In this manner, control data were obtained which should indicate any progressive change in the properties of the samples as a result of handling or treatment.

In addition to porosity values, the bulk, pore, and solid volumes were measured and recorded along with the ambient temperatures at which the data were obtained. From one to three determinations were made on each sample by each of the laboratories. The order of measurement, by participants, followed no particular sequence. The order was arranged,

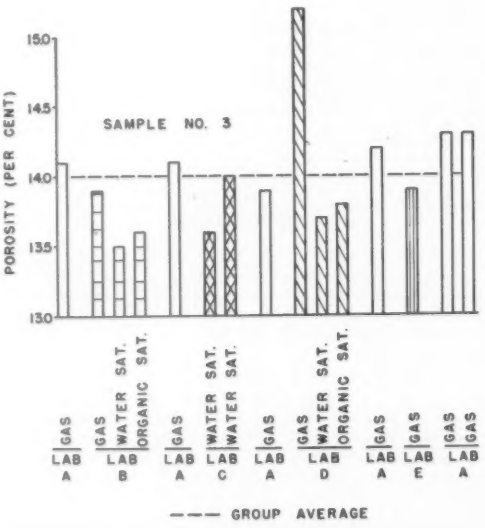

FIG. 3 — CORE SAMPLE POROSITY.

*The Atlantic Refining Co., Magnolia Petroleum Co., Phillips Petroleum Co., and Stanolind Oil and Gas Co.; General Petroleum Corp. of California also entered the program at a later date.

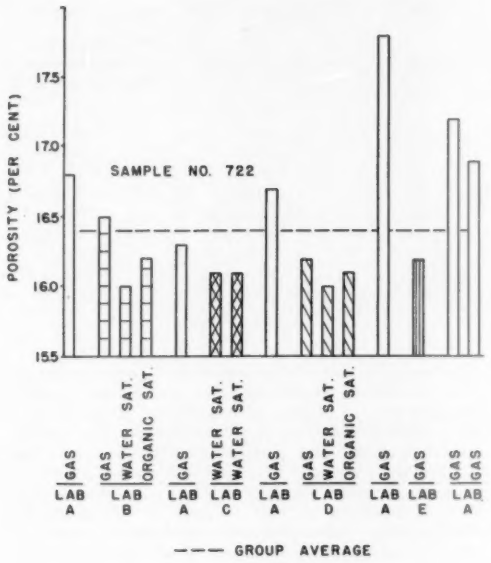

FIG. 4 — CORE SAMPLE POROSITY.

however, to permit the Magnolia Laboratories to make control measurements alternately with the other laboratories, as previously mentioned.

In order to furnish additional control data on the samples, weights of the samples were obtained by each laboratory prior to its porosity determinations and immediately prior to shipment. Weighings were also made at other times. Determinations of the gas permeabilities were made periodically throughout the investigation by the Magnolia Laboratories.

METHODS OF POROSITY MEASUREMENT*

Laboratory A employed the Kobe Porosimeter for porosity measurement. Both the solid and bulk volumes are determined in the instrument, bulk volume by mercury displacement and solid volume by air displacement. The fractional porosity is obtained by dividing the difference between the bulk and solid volumes by the bulk volume.

Laboratory B employed three methods for porosity determination. These are as follows:

1. Gas Method

   The solid volume of the sample is determined directly in a Modified Bureau of Mines Boyles Law Air Porosimeter. The bulk volume is determined by mercury displacement. Subtracting the solid volume from the bulk volume and dividing this result by the bulk volume yields the fractional porosity.

2. Water Saturation

   The pore volume is determined from the difference between the weights of the dry sample and the sample saturated with distilled water, divided by the density of the water. Determination of the bulk volume is made by weighing the water-saturated sample in air and again weighing it submerged in water. The difference between these weights divided by the density of water yields the bulk volume. The ratio of the pore volume to the bulk volume is the fractional porosity.

3. Organic Liquid Saturation

   This method is identical with that of No. 2 except that tetrachlorethane is used in place of water.

Two methods of porosity measurement were employed by Laboratory C.

1. The solid volume is determined by the difference in weights of the dry sample (in air) and the sample saturated with and suspended in water, divided by the density of water. The bulk volume is determined from the mercury displacement produced by the water saturated sample. The fractional porosity is the difference between the bulk and solid volumes divided by the bulk volume.

2. According to the second method, the pore volume is determined by the difference between the weight (in air) of a water-saturated core sample and the weight of the dry sample, divided by the density of water. This result, divided by the bulk volume, as determined by Method No. 1, yields the fractional porosity.

Laboratory D employed three methods of porosity measurement. These are as follows:

1. Gas Method

   The bulk volume is determined by weighing the core saturated and suspended in saturant. The difference in these weights divided by the density of the saturant gives the bulk volume. The solid volume is determined directly by a gas expansion porosimeter. The porosity fraction is given by the bulk volume minus the solid volume divided by the bulk volume.

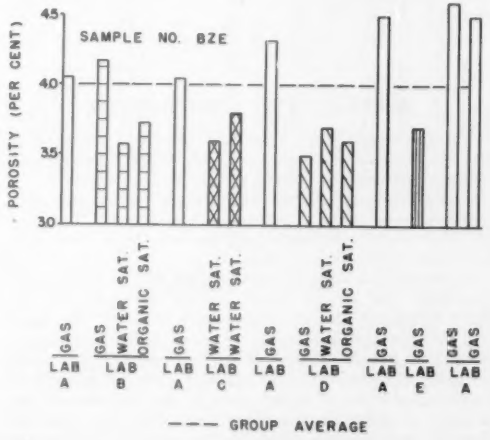

FIG. 5 — CORE SAMPLE POROSITY.

*References given at end of paper.

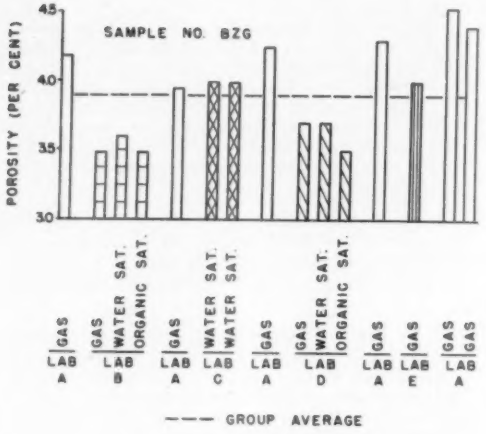

FIG. 6 — CORE SAMPLE POROSITY.

2. Water Saturation

In this method the pore volume was determined from the difference in weights of the water-saturated sample in air and the weight of the dry sample in air. This weight difference (corrected for liquid density) yields the pore volume. This pore volume divided by the bulk volume, determined as described in the gas method procedure above, yields the fractional porosity.

3. Organic Liquid Saturation

This method is identical with that of No. 2 above except that the hydrocarbon, tri-isobutylene, is used in place of distilled water for both the pore- and bulk-volume determinations.

Laboratory E also used the Kobe Porosimeter for porosity measurements. The procedure is the same as that described above for Laboratory A, except that helium was used in place of air.

RESULTS AND CONCLUSIONS

The core sample porosity-check program was completed as planned. Porosity measurements of ten selected, natural and synthetic, core samples were made by five laboratories.

During the course of the investigation, the samples were subjected to a variety of methods of measurement. These included physical measurement, gas, and saturation (with both water and organic liquids) methods.

In general, the measured values were in reasonably good agreement. The results of the porosity measurements are shown graphically in Figs. 1 through 10, inclusive. The measured values, expressed in terms of per cent porosity, are shown along the ordinate and the number of measurements are shown along the abscissa. These are arranged from left to right in chronological order of measurement by the participants. The average, or mean, porosity value and the average deviation from the mean porosity values for the samples are shown in Table II.

Table II — Results of Porosity Measurements

Sample Number	Mean Porosity Value (%)	Average Deviation from Mean Porosity (%)
1	17.5	± 0.5
2	28.4	± 0.4
3	14.0	± 0.3
4	30.3	± 1.0
BZE	4.0	± 0.3
BZG	3.9	± 0.3
61-A	28.4	± 0.5
722	16.4	± 0.4
1123	32.6	± 0.6
1141-A	19.4	± 0.4

The average deviation of porosity from the mean or average values for all samples was ±0.5 porosity per cent. Lack of agreement was the greatest for sample No. 4, which was a friable, high-permeability, sandstone sample. The average deviation from the mean porosity value for this sample was ±1.0 porosity per cent. The largest difference of values for sample No. 4 was 5.6 porosity per cent; *i.e.*, a variation from 26.8 to 32.4 porosity per cent. Exclusive of this sample, the largest variation of individual values occurred for sample No. 1123. The individual measurements of porosity in this case exhibited a total range of 2.1 porosity per cent; *i.e.*, from 31.7 to 33.8 porosity per cent.

The results of the porosity measurements are considered fairly good, and the variations which occurred were not of the order of magnitude that was suspected when this program

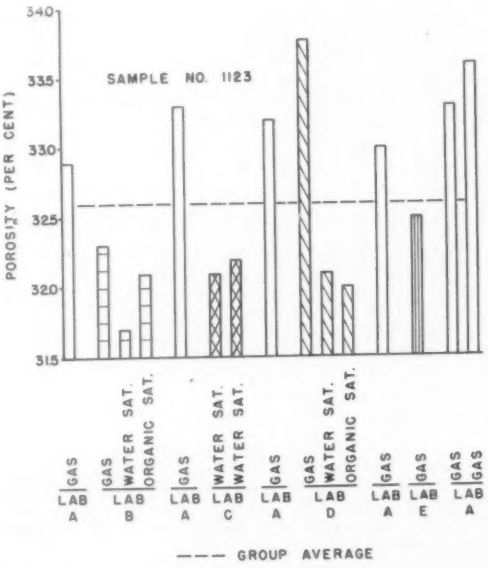

FIG. 7 — CORE SAMPLE POROSITY.

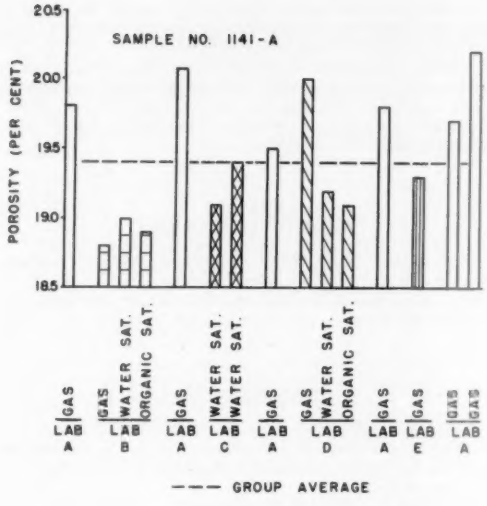

FIG. 8 — CORE SAMPLE POROSITY.

A weight check maintained on the samples showed that, with the exception of three samples, the weights remained essentially constant. Samples No. 3, 4, and 1123 showed a progressive decrease in weight which was evidently caused by the loss of solid material from the samples with handling. This loss of material was also readily apparent in the trend of the bulk and solid volume measurements on these samples. The decrease was most pronounced in the case of sample No. 4, a very friable high-permeability sandstone sample. As was initiated. However, it is well to emphasize that the samples selected were an idealized group, in that, as far as is known, they were relatively immune to reaction with the materials which made contact with them during the porosity measurements. Thus, the investigation resulted in being, primarily, a check of methods and instruments. The differences actually observed between the various methods, while small, are considerably greater than the individual reproducibility of each method. This paper makes no effort to account for these differences, nor does it present any estimate of the relative reliability of the various methods.

Since the porosity values shown in Figs. 1 through 10, inclusive, are derived from the measured quantities, bulk, solid and pore volumes, it is then evident that the variations experienced in the porosity values are the result of a combination of variations in these quantities. The determinations of bulk volume were the most reproducible of the quantities measured. However, this excludes the method of caliper measurement, since this method inherently yields a value which is too large. The lack of reproducibility of the solid and pore volume measurements was of the same order of magnitude.

In general, the gas methods gave slightly higher values, on the average, than liquid saturation methods. This may be partially due to the presence of adsorbed gases in the Boyle's Law Method or to lack of complete saturation of the samples in the saturation methods, or a combination of both.

It is apparent from this investigation that the problem of reproducibility of porosity measurement is not as serious as was considered possible at first. This is true at least for samples not affected by the materials used in the method of measurement. It is believed that, when made with reasonable care, future porosity measurements by the methods described can be expected to agree within the same order of magnitude as reported herein. This does not include measurements, by water saturation techniques, on samples having high clay contents, or on samples for which complete extraction of the contained crude oil has not been achieved.

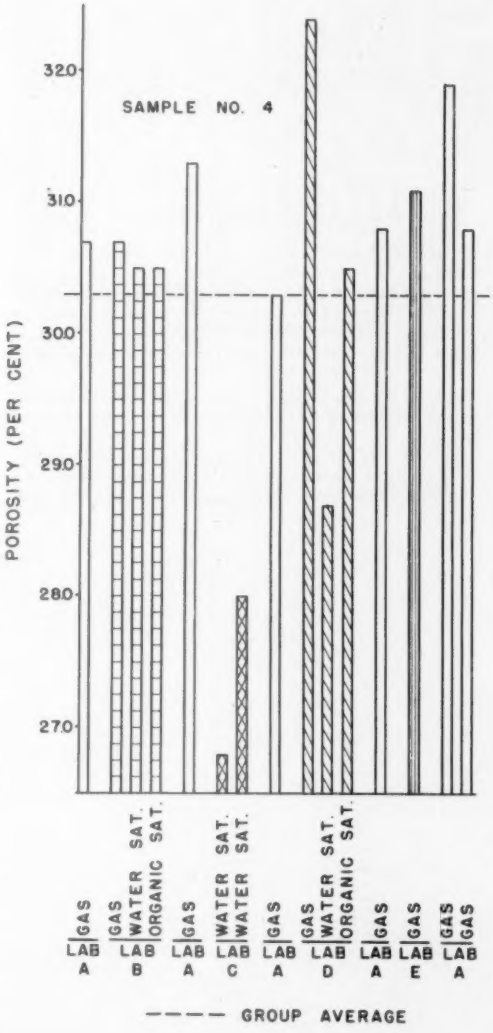

FIG. 9 — CORE SAMPLE POROSITY.

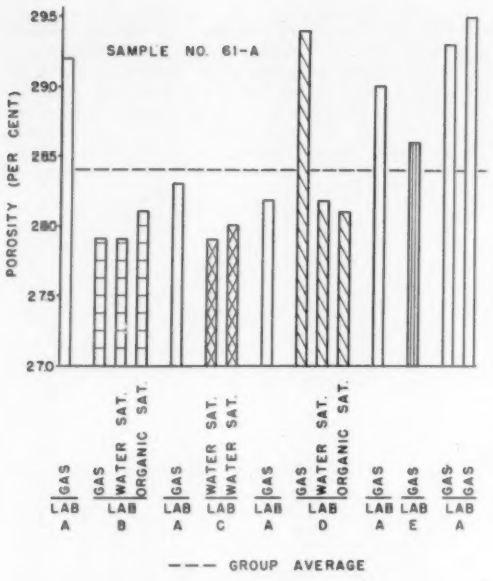

FIG. 10 — CORE SAMPLE POROSITY.

a matter of interest, it might be noted that the weight measurements obtained by the participating laboratories were very consistent.

Gas permeabilities of the samples were measured periodically during the investigation by the Magnolia Laboratories. The permeabilities were fairly constant throughout the investigation. Variations which occurred for two of the samples were probably due to measuring equipment difficulties, and not to an actual change in the samples.

Ambient temperatures occurring at the time of the porosity measurements were recorded; however, since the temperatures were essentially the same for all the measurements, slight variations in temperature were not considered in the compilation of results.

ACKNOWLEDGMENT

The authors are grateful to The Atlantic Refining Co., General Petroleum Corp., Magnolia Petroleum Co., Phillips Petroleum Co., and Stanolind Oil and Gas Co., for permission to publish this paper.

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Although the following list is not intended to be a complete bibliography on the subject, these references are included to furnish the reader with additional sources of information on porosity measurement.

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THE GUARD ELECTRODE LOGGING SYSTEM

JOHN E. OWEN, GEOPHYSICAL RESEARCH CORP., TULSA, OKLA., AND WALTON J. GREER, HALLIBURTON OIL WELL CEMENTING CO., HOUSTON, TEX., MEMBER AIME

ABSTRACT

The guard electrode system measures the resistivity of formations by employing a thin disk of current which is caused to flow perpendicular to the bore hole. The control of this current disk is obtained in a brute force manner through the use of relatively long equipotential electrodes above and below the measuring electrode.

The log obtained from the system is free of "lag," "plateau," "shadow," "reflection" and other distortions evident on conventional logs. The proportionate contributions of the hole size and invaded zone resistivity to the apparent resistivity reading are reduced when the mud and filtrate resistivities are lower. Thus, the guard system favors the use of conductive muds.

The mathematical development of the theory is given in an appendix. Equations are derived to evaluate the effects of mud resistivity, hole size, invaded zone resistivity and depth, and the true formation resistivity.

Sample logs from several provinces are reproduced and compared with conventional electric logs to illsutrate the much greater detailed lithology that can be presented by the guard electrode system.

INTRODUCTION

With increased ability of those in the petroleum industry to analyze formation characteristics from electrical resistivity data, there has become apparent the need for more precise measures of that parameter.

The measurement of the resistivity of a homogeneous and isotropic material can be made simply when the body of the material is infinite in all dimensions and the measuring electrodes can be placed within the body. In such a case, the current leaving an electrode follows a spherical distribution and the mathematical expression for the potential level at any distance from that electrode can readily be derived.[1,2]

If it is considered that the active electrodes are within a bore hole filled with mud of a resistivity different from that of the formation, the current does not flow in a spherical pattern near the current source or sink, and the calculations of potential levels become more difficult. The additional consideration of a section of formation invaded by mud filtrates, and thus having resistivity different from either that of the mud, the adjacent formations or of the undisturbed formation, makes the mathematical problem extremely complex. Should the vertical dimensions of the formations be considered as finite, the problem becomes so complex as to preclude reasonable solution. Yet, even these considerations have not described adequately the conditions encountered in a large proportion of the wells to be studied.

In efforts to evaluate the effects of the various conditions, combinations of two, three, and four electrode logging configurations of the conventional types have been used. The resulting logs have left much to be desired in some provinces. It has become apparent that the use of such configurations will not result in adequate measurements being made, particularly in cases where the formation is composed of thin sections.

If all the current of a resistivity measuring circuit is made to flow through the formation opposite the exploring electrode, many of the shortcomings of the conventional measuring system are eliminated. In the guard electrode method of electrical well logging to be discussed in this paper, the current is so controlled by causing it to flow in a thin disk normal to the axis of the logging tool.

EARLY HISTORY

The guard electrode method of electrical well logging in its early years was a joint development by the Geophysical Research Corp. and the Amerada Petroleum Corp. The method was first experimentally investigated by means of model studies. The results of these studies indicated that current focusing systems properly applied to electrical well logging

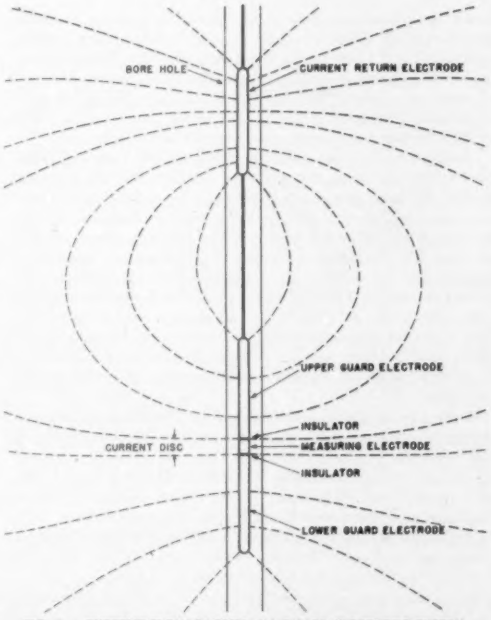


FIG. 1 — CURRENT FLOW PATTERN IN GUARD ELECTRODE SYSTEM.

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch June 22, 1951. Paper presented at the Petroleum Branch Fall Meeting in Oklahoma City, Okla., Oct. 3-5, 1951.

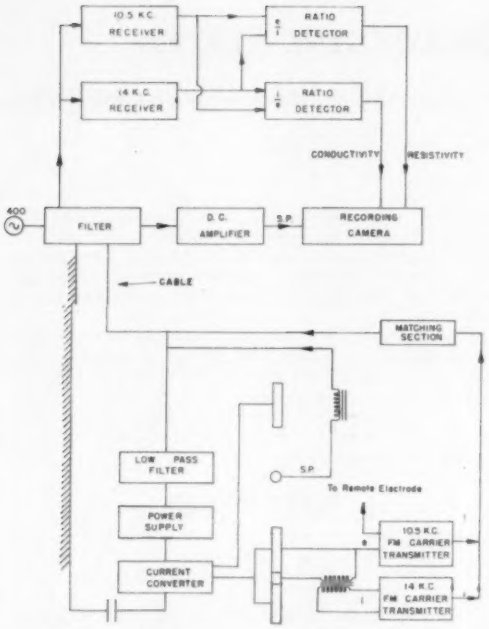


FIG. 2—BLOCK DIAGRAM OF INSTRUMENTATION EMPLOYED IN GUARD ELECTRODE LOGGING.

might have great possibilities in improving existing methods, and the decision was reached to build the necessary logging equipment and to carry the work into the field. This occurred in the period just preceding World War II. Critical shortages of materials during the war made the acquisition of field equipment extremely difficult; and as a result, actual field trials were not made until after the end of the war.

Some advantage was taken of these delays, however. Various current focusing systems were studied and the one that showed the most promise was selected for a field trial. There was developed during this period a wholly electronic system for supplying electrical power to the focusing electrode system and for combining for suitable recording at normal logging speeds the intelligence transmitted to the surface over the logging cable. This last phase of the work included, among other things, the development of an analog type of computer. This computer is an electronic instrument called a ratio detector, a device which permits the simultaneous logging of the resistivities and conductivities of formations traversed by the bore hole.

In the period that guard electrode well logging was carried out as an experimental project by the Geophysical Research Corp. and the Amerada Petroleum Corp., 31 wells were logged for a total of approximately 175,000 ft. Most of these wells were located in Oklahoma, in the West Velma, Sholem-Alechem, and Northwest Knox Fields. Other wells that were logged were in the Bloomington Field in the Gulf Coast of Texas, in the Fargo Field in North Texas, in the Barnhart Field in West Texas, and in three fields in California.

During the year 1950, the Halliburton Oil Well Cementing Co. assumed the development of a commercial logging device based on the principles proposed by Geophysical Research Corp. This involved adapting the instrumentation to a single-conductor transmission system instead of the multiple-conductor system used in the early development.

ELEMENTS OF GUARD ELECTRODE METHOD OF ELECTRICAL WELL LOGGING

The principles of the guard electrode logging device are illustrated in Fig. 1. All surfaces of the bottom electrode assembly are kept at essentially the same potential. This guard electrode assembly is made up of an upper guard electrode, a measuring electrode, and a lower guard electrode. An alternating current is passed between the bottom electrode assembly and the current return electrode. The path the current takes in going from the guard electrode assembly to the current return electrode through the earth is indicated by the dotted lines. The all-important feature of this system is that the current from the measuring electrode flows outwardly in essentially a horizontal direction for a considerable distance, and hence is confined to a disk-shaped space having a thickness approximately the same as the length of the measuring electrode. Variations in earth resistivity within this disk-shaped region control the amount of current flowing from the measuring electrode. It is desirable that variations in earth resistivity in the neighborhood of the current return electrode do not affect the resistivity or conductivity measurements that are obtained. This is accomplished by proper instrumentation, as will be shown.

The electrical measures needed from this system to provide the desired readings of resistivity and conductivity consist of (1) a measurement of the current emitted by the measuring electrode, and (2) a measurement of the voltage between this electrode and a point remote from any area of current concentration. A resistivity value is obtained by recording the ratio of the voltage between the measuring electrode and this distant point to the current passing into the earth from the measuring electrode. A conductivity value is obtained by recording the ratio of the current from the measuring electrode to the voltage between it and the distant point. Because the measured voltage is from the measuring electrode to a remote point which does not change in potential, the resistivity and conductivity values which are determined are not influenced by resistivity changes near the current return electrode in the hole. The reference depth is the depth of the measuring electrode. The geometry of this electrode system thus compares in simplicity with that of the single or point electrode.

INSTRUMENTATION

The instrumentation employed to furnish the necessary current to the electrode system and to measure the voltage and exploring current values and transmit them to the surface over a single-conductor cable is shown in block form in Fig. 2.

Located within the guard electrode assembly are all the electronic circuits required. The power necessary for these circuits is supplied by a gasoline engine driven 400-cycles-per-sec alternator located on the logging truck. The 400-cycles-per-sec current is impressed onto the line in a filter section as shown. In the tool, this current is directed by a low pass filter first through the power supply which provides the necessary heater and plate potentials for the various electronic tubes. From the power supply, the current is directed through a current converter which supplies the guard electrode system with current at 200 cycles per sec. The current then passes

through a condenser to the sheath of the cable and returns to the alternator. The condenser blocks the SP signal from the sheath.

The total 200-cycles-per-sec current flows between the guard electrode and a current return electrode located some 60 ft up the cable from the exploring electrode. The exploring current is measured by a vacuum tube circuit which requires an extremely small signal.

The potential of the guard electrode is measured by another vacuum tube circuit connected between the guard electrode and a reference electrode located about 200 ft up the cable.

The measures of the exploring current and the potential modulate in frequency oscillators with center frequencies of 14 kc and 10.5 kc respectively. These carrier frequencies are impressed onto the single-conductor cable by a matching section which raises the power level of the combined signals and matches the impedance of the line.

At the surface, the carrier frequency signals are removed from the cable by the filter section and directed to their respective receivers. From these, current and voltage signals corresponding to those measured in the tool are obtained and directed to the ratio detector. The ratio detector provides a current corresponding to the resistivity or to the conductivity of the formation being logged. The output depends, of course, upon which of the current and potential measures is used as the numerator and which the denominator.

Provision is made for the logging of an SP curve simultaneously with that of the conductivity and resistivity. The signal is picked up by a separate electrode and applied to the conductor of the cable through a high inductance choke. In present tools the SP is located 30 ft above the exploring electrode. This offset is made necessary by the mass of exposed metal of the guard electrode which short circuits the SP in the vicinity of the exploring electrode. On the finished log, the SP curve is shifted the corresponding 30 ft in order to present the log at its proper depth. The location of the electrode prevents the logging of SP over the bottom section of the hole. The distance missed is 30 ft plus half the length of the guard electrode.

Graphs of the resistivity, conductivity, and SP values are recorded in a conventional electric logging camera.

THEORETICAL RESPONSE OF THE GUARD ELECTRODE SYSTEM

The proportionality factors by which the values measured are converted to resistivities and conductivities are, of course, the calibration factors which must be determined for the electrode configuration that is used. In the first well that was logged with guard electrode equipment by Amerada, a thick shale section of uniform resistivity was found. The first calibration of the guard electrode equipment was thus empirically obtained by assigning such a value to the calibration constant for the guard electrode equipment that agreement was reached between the guard electrode recorded apparent resistivity in this shale section and the corresponding apparent resistivity recorded on the conventional electrical log that was taken on the same well.

Computations of this calibration factor were later made, as were also extensions of the theory to include the effects of the resistivity of the fluid in the bore hole and the resistivity of the invaded zone.*

Certain of the formulæ that have been derived are of sufficient interest that they may be called to attention here. It should be understood that the derivation in the appendix is based on the assumption that the electrode has the shape of a prolate spheroid. This is considered to be a sufficiently close approximation to the actual shape of the electrode that formulæ thus developed are applicable. The following notation is used:

$2c$ = overall length of guard electrode assembly
$2b$ = length of measuring electrode
$2a$ = diameter of measuring electrode
$2a_2 = d$ = diameter of bore hole
$2a_3 = d_i$ = diameter of invaded zone
ρ_a = apparent resistivity as recorded on guard electrode log
ρ_m = resistivity of fluid in bore hole
ρ_i = resistivity of invaded zone
ρ_t = resistivity of uninvaded formation
I_o = current from measuring electrode
V_o = voltage between measuring electrode and distant ground reference

One equation of interest relates the resistivity of a formation of large extent in which the guard electrode assembly is buried, the voltage on the electrode, and the current from the measuring electrode. This determines the calibration factor for the electrode. For this case,

$$\rho_t = \rho_a = \frac{4\pi b}{ln\,\dfrac{c+k}{a}} \cdot \left(\frac{V_o}{I_o}\right) \quad . \; . \; . \quad (1)$$

Another equation of interest is one expressing, in the case of no invasion, the relationship between the apparent resistivity of a formation, its true resistivity, and the resistivity of the mud in the bore hole. Here,

$$\frac{\rho_a}{\rho_m} = 1 + \left(\frac{\rho_t}{\rho_m} - 1\right)^{\dfrac{ln\,\frac{2(c_2+k)}{d}}{ln\,\frac{c+k}{a}}} \quad . \quad (2)$$

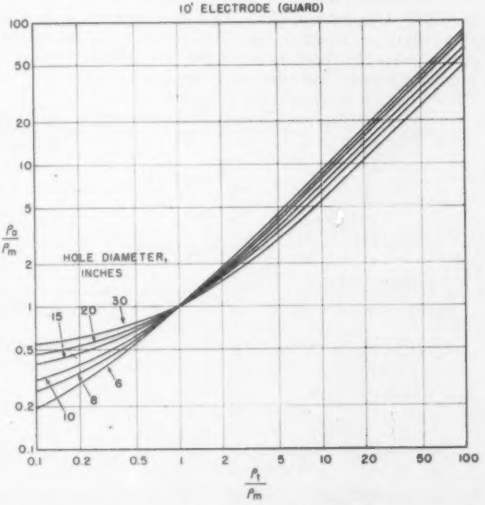


FIG. 3 — EFFECT OF HOLE SIZE AND MUD RESISTIVITY ON VALUES MEASURED BY GUARD ELECTRODE.

*This work was first done by A. Wolf and J. E. Owen of the Geophysical Research Corp., and later by Guy O. Buckner, Jr., of the Halliburton Oil Well Cementing Co. The results that were obtained were essentially equivalent. In the appendix of this paper, the derivation by Buckner is given.

The curves of Fig. 3 are calculated from Equation (2) and illustrate the effect of the bore hole diameter and the mud resistivity upon the readings of a system employing a total guard electrode length of ten ft and a measuring electrode of three in.

For the case in which there is invasion:

$$\frac{\rho_a}{\rho_m} = 1 + \left(\frac{\rho_t}{\rho_m} - 1\right) \frac{ln \frac{2(c_2+k)}{d}}{ln \frac{c+k}{a}} + \left(\frac{\rho_t}{\rho_m} - \frac{\rho_i}{\rho_m}\right) \frac{ln \frac{2(c_2+k)}{di}}{ln \frac{c+k}{a}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

c_2, c_0, and k are defined in the appendix.

From Equation (2), it is apparent that the relative contribution of formation resistivity to the reading of apparent resistivity increases as the mud resistivity decreases. Likewise, from Equation (3), the relative contribution of the invaded zone can be made less by reducing its resistivity. This could be realized, of course, by reducing the filtrate resistivity.

Still another equation of interest is the one giving the thickness t of the current measuring disk at a distance r from the axis of the bore hole, and for the case in which the guard electrode assembly is located within a thick bed. Here,

$$t = 2b \sqrt{1 + \frac{r^2}{c^2 - a^2 - b^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and for the usual case in which $c \gg a$, and $c \gg b$,

$$t = 2b \sqrt{1 + \frac{r^2}{c^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

to a sufficiently close approximation.

Fig. 4 illustrates the thickening of the current disk corresponding to equipment in which $c = 10$ ft, $a = 1\frac{1}{2}$ in., and $b = 1\frac{1}{2}$ in. Here it is seen that the current disk doubles in thickness at a distance of 17.3 ft from the axis of the electrode.

The thickening of the measuring current disk for short guard electrodes occurs much faster with radial distance than for long guard electrodes. The use of long and short guard electrodes thus shows promise of being the means for making resistivity measurements at different radial distances from the bore hole. Calculations which must be considered to be only approximate at this stage of the development of the method indicate that the depth of investigation may thus readily be controlled from a few inches to a few feet.

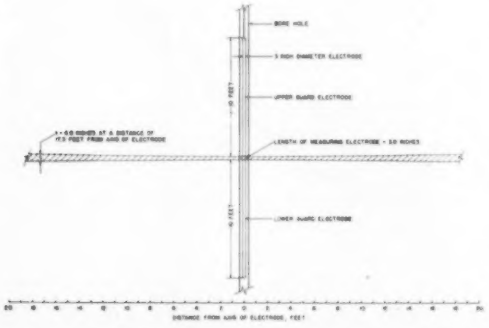


FIG. 4 — DISTRIBUTION OF CURRENT FROM MEASURING ELECTRODE OF GUARD ELECTRODE SYSTEM IN A HOMOGENEOUS, ISOTROPIC MEDIUM.

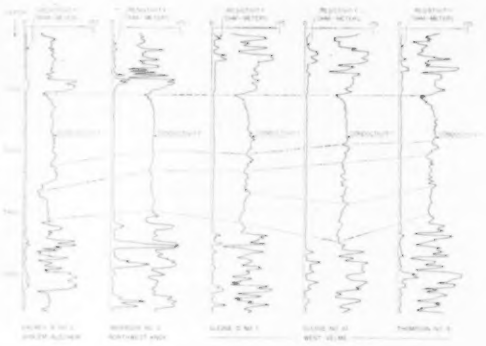


FIG. 5 — CONDUCTIVITY CORRELATIONS BETWEEN WELLS IN THREE OKLAHOMA OIL FIELDS.

The values recorded by the system will be exactly as calculated above so long as the actual conditions do not depart from those assumed. The mathematical equations presented were all derived with the considerations that the guard electrode has the surface of a prolate spheroid and that the entire surface is maintained at the same potential. These conditions are not held precisely.

In practice, the electrode has a cylindrical surface. For the configurations now being used, where the length of the electrode is large compared to the diameter, this difference in surfaces need not be considered. It is probable that logs made with configurations using very short guard lengths will be found valuable for the solutions of some problems. If guard lengths of the order of a few inches should be employed, correction factors would be required. No method has yet been devised to calculate such factors. They will be supplied by controlled model studies if the continued mathematical study fails to produce them.

The potential of the surface of the measuring electrode is always less than that of the guard electrode. This results from the necessity of there being a finite resistance in the current measuring circuit between the guard electrode and the measuring electrode through which the exploring current must flow. The proportional difference in potential between the electrodes in such a system is a function of the resistance of the electrode, which in turn is a function of the mud and formation resistivities. In present tools, the resistance between the surfaces is 0.05 ohms. This results in such small differences of potentials that for all values of mud and formation resistivities of 0.2 ohm-meter, or greater, the resulting errors in recorded values are less than 5 per cent. With lower mud and formation resistivities, the error increases rapidly. If the electrode assembly should be buried in a material of 0.09 ohm-meter resistivity, the recorded value would be 25 per cent greater than true.

Consideration thus far has been given only to the logging of thick beds. The problem of thin beds, however, has proved to be one for which some of the most outstanding results have been obtained with guard electrode equipment. The model work that was first done with the guard electrode indicated, and later field work has verified, that the response of the system to thin beds is greater than for any other logging system known to be in use. Furthermore, there are for the guard electrode no shadow zones of the type associated with the

so-called lateral device. The boundaries of thin beds, thick beds, and beds of intermediate thickness are sharply defined without the spurious responses of geometrical origin so common to conventional logs. For reasons such as these, the guard electrode has been found to provide a superior tool for correlation, for the recognition of conditions of inhomogeneity, and for locating accurately the depths of resistivity boundaries.

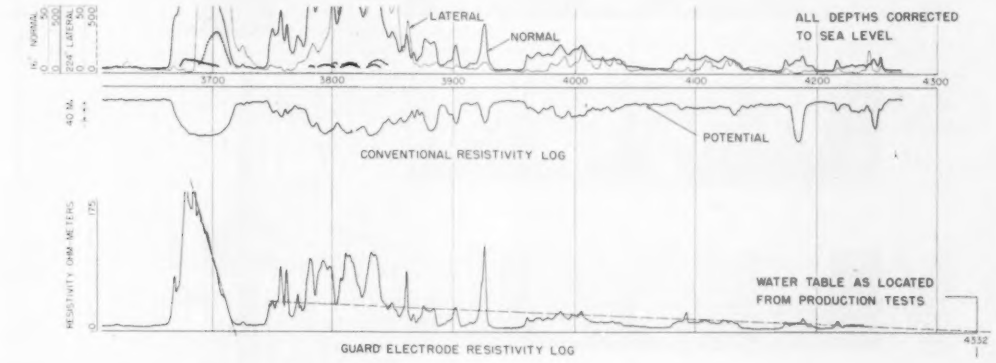
SAMPLE GUARD ELECTRODE LOGS IN THE MID-CONTINENT AREA

In Fig. 5 are reproduced sections of guard electrode logs made in Southern Oklahoma. In this figure, both the resistivity and conductivity traces of the logs are reproduced. All of these conductivity logs have the same sensitivity. These logs are from three fields, separated by distances of approximately 25 miles. The correlations between fields that are indicated in the figure were made by using the conductivity logs, and without benefit of any geological information on the wells they represent. There are large differences between the recorded resistivity values in corresponding sections in the different wells, and consequently the resistivity logs were of little value in field-to-field correlations. Several other correlations between the wells in the different fields were made by using portions of the conductivity logs not reproduced.

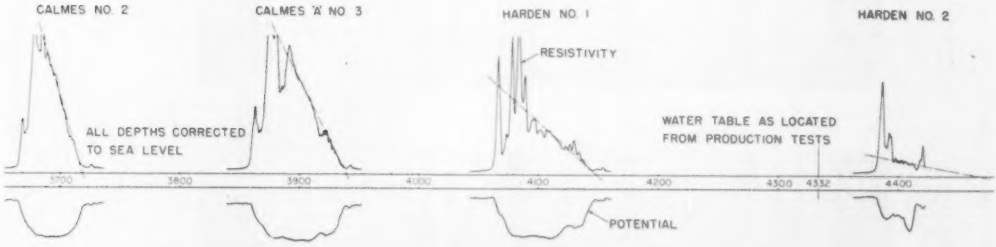
Three logs from the West Velma Field are included in the figure to illustrate the character that the guard electrode conductivity logs usually show in shale sections. The character in the shale section is seen to have significance, for by means of it, correlations within these sections can be established. For purposes of geological correlation, the guard electrode logs were found to be markedly superior to the standard electrical logs of these wells.

Fig. 6 illustrates some features of guard electrode logs that have direct bearing on reservoir studies. No conductivity logs are included in Fig. 6. The guard electrode log on the Calmes No. 2 shows a sand section from approximately 3,670 to 3,720 ft. This section has a definite resistivity gradient. Immediately below this is a shale section approximately 25 ft in thickness. Below this, there is a broken sand section or several sands through which a gradient may be drawn to the water table established for this well by production tests. Logs on other wells in the field indicate that the shale section from 3,720 to 3,745 ft in the Calmes No. 2 extends over the entire field, and hence, the upper sand may be considered to be a separate reservoir.

Of further interest in this connection are the logs in the lower part of Fig. 6. These are the logs of this same upper sand in four wells in Sholem-Alechem. These logs all show gradients, and the gradients are a function of the depth of the sand, or possibly its location with respect to the water table. It is not the purpose of, or within the scope of, this paper to



RESISTIVITY LOGS OF CALMES NO. 2, SHOLEM ALECHEM FIELD



GUARD ELECTRODE RESISTIVITY LOGS OF UPPER SIMS SAND, SHOLEM ALECHEM FIELD

FIG. 6 — LOGS IN SCHOLEM ALECHEM.

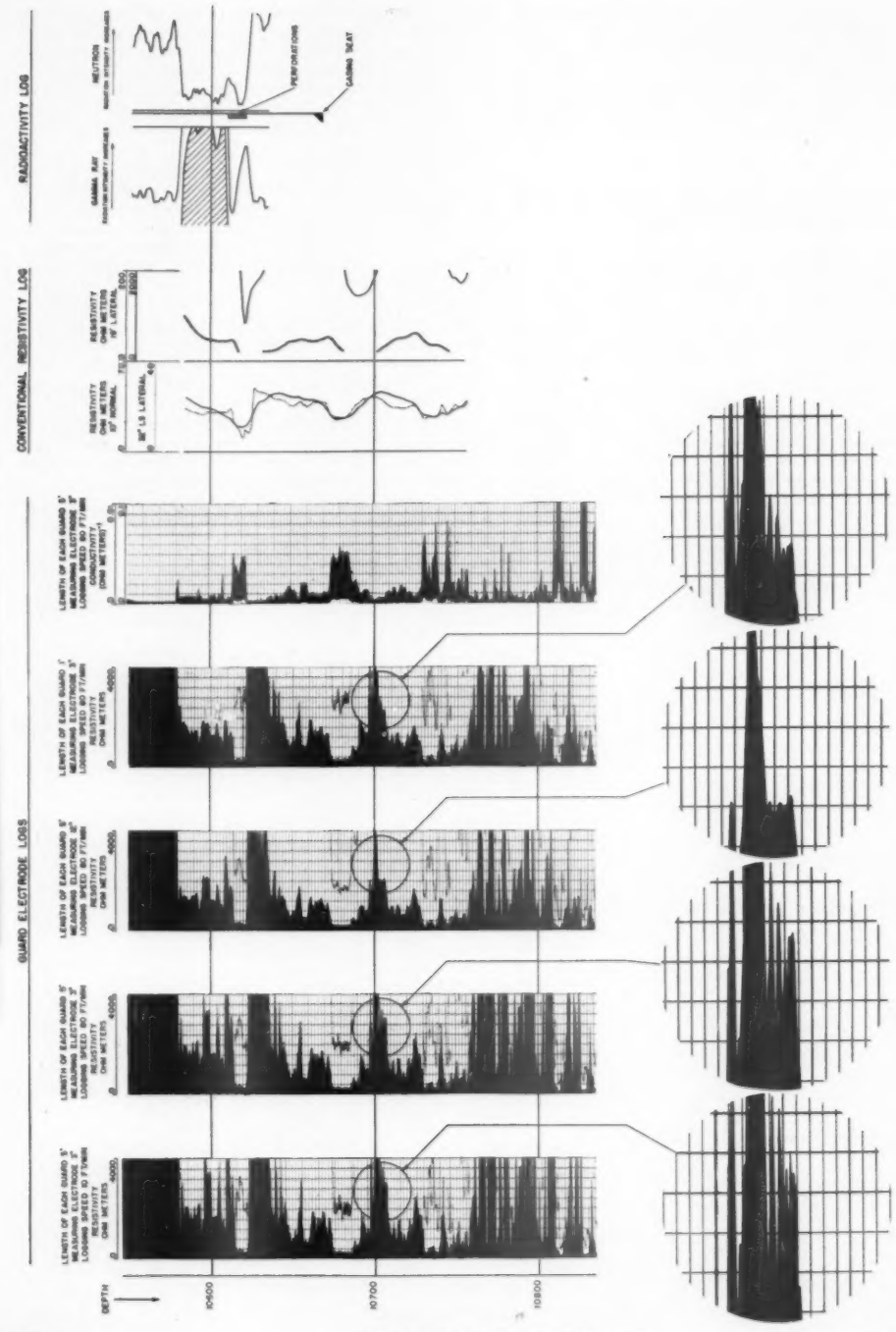


FIG. 7 — GUARD ELECTRODE. CONVENTIONAL RESISTIVITY AND RADIOACTIVITY LOGS, AMERADA D. L. ADCOCK NO. 1, DAWSON COUNTY, TEX.

discuss the significance of these gradients; but, rather to point out that the ability of the guard electrode system to give measurements characteristic of the exact depth at which the measurements are made allows study of reservoir problems within relatively thin sand bodies. The standard electrical logs on these same wells do not show the gradients in the upper sand, although the gradient from 3,750 to 4,332 ft can be determined from the standard log probably as well as from the guard electrode log.

SAMPLE GUARD ELECTRODE LOGS IN THE WEST TEXAS AREA

Guard electrode logs were run in the Amerada No. 1, D. L. Adcock well in Dawson County, Tex. Portions of these logs are reproduced in Fig. 7. Reproduced, also, are the neutron, gamma-ray, and conventional electrical logs for as much of the same section of the hole as these logs are available. The resistivity of the mud was reported as 0.18 ohm-meters at the bottom-hole temperature.

Three combinations of guard and measuring electrode lengths were used for these logs. One log was run with short guards, each guard one ft in length and with a measuring electrode three in. long. A log was run with five-ft guards and a measuring electrode of three in. Another log was run with five-ft guards, but with a 12-in. measuring electrode. Three of the guard electrode logs were run at a logging speed of 80 ft/min. In order to test the possible effect of logging speed on the quality of the log obtained, the log with the five-ft guards and the three-in. measuring electrode was rerun at a logging speed of only 10 ft/min. The two logs of the same type run at the different speeds are quite similar, except for a little additional detail in the log taken at the slower speed. These differences in detail may be seen in the enlarged portions of the logs. A considerable part of the fine detail obtained with the three-in. measuring electrode is missing in the log made with the 12-in. measuring electrode. The detail given by the 12-in. measuring electrode may be sufficient for most purposes, but it is apparent that the logs would lose much of their interpretative value if the thickness of the current measuring disk were made appreciably greater than 12 in.

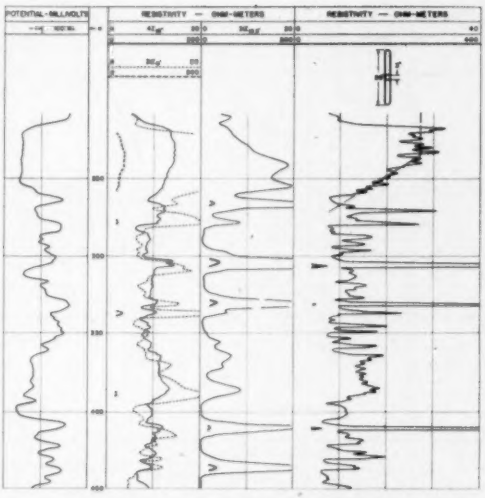


FIG. 9 — COMPARISON OF LOGS FROM GUARD ELECTRODE AND CONVENTIONAL SYSTEMS IN WILCOX SECTION, AUSTIN COUNTY, TEX. (CONTINUED FROM FIG. 8.)

The conductivity log is also reproduced in Fig. 7. Boundaries between shale and lime sections are very sharply defined. Broken, water bearing, permeable zones in the lower portion of the guard electrode logs are clearly shown. The excellent detail of guard electrode logs such as these points to a need for the best possible depth control in taking cores and for all methods of logging and in all steps in well completions in order that full advantage may be taken of the detailed information that the guard electrode gives.

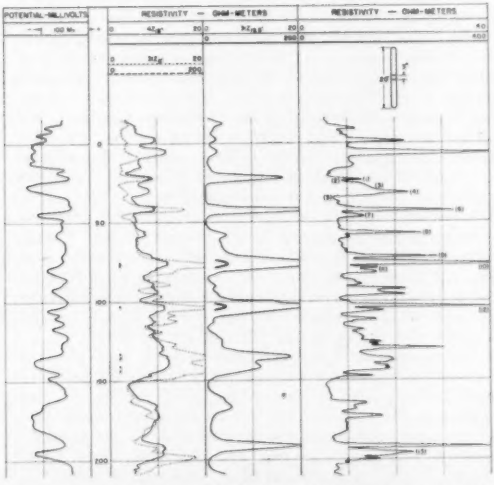


FIG. 8 — COMPARISON OF LOGS FROM GUARD ELECTRODE AND CONVENTIONAL SYSTEMS IN WILCOX SECTION, AUSTIN COUNTY, TEX.

SAMPLE LOGS FROM SOUTH TEXAS

Fig. 8 shows a conventional electric log and a guard log over a Wilcox section in Austin County, Tex. Curves from three resistivity measuring configurations are shown on the conventional log. A four-electrode arrangement with an effective spacing of 18 in. (designated 4Z18″) is used for the correlation curve. The other configurations are of the three-electrode type and have spacings of six ft (designated 3IZ6′) and 19.5 ft (designated 3IZ19.5′). The guard electrode is 20 ft in length and has a measuring electrode of three in. By a close examination of the logs, the relative presentations can be evaluated.

The SP curve indicates the presence of a sand body between about 0023 and 0033. The long three-electrode curve does not give any indication of resistivity within this section. The entire section appears to be in a shadowed zone insofar as the 19.5′ curve is concerned. There are some indications from the 4Z18″ and 3IZ6′ curves that there may be a resistive streak near the bottom of the sand section. The core for this section was described as six in. of lignite, one ft of shale, four ft of

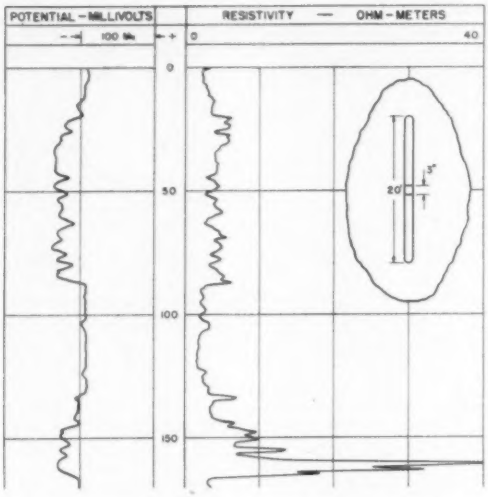


FIG. 10 – EXAMPLE OF GUARD ELECTRODE LOG IN MIOCENE SAND.

sand with oil, and then a mixture of quartzite-like sand, shale and lignite for four ft and then shale. Such detail cannot be read from the conventional log. On the guard record, the area marked (1) is probably the six in. of lignite, (2) is the one ft of shale, (3) is the four ft of oil sand, (4) and (5) are the hard section and the shale, respectively.

At 0042 to 0046, there is a potential anomaly that should indicate a sand body. On the conventional log, the resistivity measures are meaningless because all curves are in a shadowed zone resulting from a highly resistive section at 0042. The reflection on the 3IZ6′ curve is at 0048 and on the 3IZ19.5′ at 0060. The guard log shows the highly resistive sections to be less than two ft in thickness at (6). Immediately below this the resistivity of the sand section is shown at (7). This curve could readily be used to determine the thickness of the sand to be about three ft.

At (8) on the guard log, there is indicated a thin highly resistive streak that is not evident at all on the conventional log. Reading from the guard log, there are defined thin highly resistive sections at (9) and (10) and a sand at (11) with perhaps a total of two ft capable of producing fluid. The conventional log treats this entire section as though there was only one resistive streak at 0075. The interpretation of the section between 0090 to 0108 from the conventional log would be difficult.

There are indications of a sand from the SP curve at 0104. On the conventional log, the resistivity values are extremely high and the resistive section appears to start slightly above the section of possible porosity. Core data show this section to be made up of a lignite streak at the top, a thin streak of hard shale and then a thin section of sand with a show of oil. Such a description can well be correlated with the guard log at (12).

A sand count of the oil-bearing section between 0134 and 0143 can better be made from the guard resistivity log than from any of the curves on the conventional log.

Within the section from 0192 to 0200, there is a section of about four ft of sand containing oil, according to the cores. This section is apparent on the guard log at (13). Such an interpretation would be difficult to make from the conventional log.

The log of this well is continued in Fig. 9. The well is being produced from the sand body shown on the log between 0212 and 0260. The conventional log shows this section to be a uniform sand body with good resistivity values. Due to the nature of three-electrode curves commonly used, it is indicated that the higher resistivity is in the lower part of this body of sand. The guard log indicates an entirely different character. Without too much imagination, it could be claimed that the upper 20 ft of this section has an average apparent resistivity of about 27 ohm-meters and then there is a distinct gradient downward in resistivity through the lower section of the sand body. This character of the resistivity curve from the guard log may well fit into a pattern of theoretical capillary action.

One more sand section shown by cores to be oil bearing that cannot be determined by the conventional log, but is defined by the guard log, is located at 0424 to 0430. The lignite at 0410 blots out all character of the 3IZ19.5′ curve for the next 20 ft.

Fig. 10 shows a section of a guard log made on a well in the Goose Creek Field of Harris County, Tex. The log illustrates the response of the guard system in water and oil-bearing Miocene sands in this area. The upper sand section contains only water; the lower produces oil. Such detail as presented on the log should allow for much more accurate determination of the producing sand count than could be read from the conventional resistivity logs having readings corresponding to averages over larger sections than the thin disk investigated by the guard system.

CONCLUSIONS

The guard records have shown that there rarely exists a formation of uniform characteristics of more than a few feet in thickness. Conventional resistivity logging configurations are not able to indicate apparent resistivities that can be evaluated reasonably except in the most simple cases. Formations located away from the one being investigated up to a distance equal to the spacing of the configuration, or more, will affect the reading. Such terms as shield, shadow, reflection, plateau, and lag are applied to these zones of distortion in the resistivity readings. In the guard system, a brute force method of controlling the investigating current into a thin disk perpendicular to the bore hole is employed. Since the effective measuring current is not allowed to pass through them, the adjacent formations do not affect the reading opposite any given section. Full resistivity value is given to a formation within inches of the boundary with another formation of large contrast in resistivity. Thus, true lithology is recorded provided disk thicknesses of 12 in. or less are used.

Due to the control of the current outward, good resistivity logs can be obtained even when highly conductive muds are used. In fact, when employing long guard lengths, the more conductive the mud, the less will be the proportionate effect of the mud column and the invaded zone on the resistivity reading. It is indicated that by employing several guard lengths, a good evaluation of these zones can be made.

The guard electrode logging system, as illustrated in the examples presented, has already demonstrated its ability to

provide superior correlation in shale sections with the conductivity log. The resistivity values recorded are characteristic of the formation directly opposite the measuring electrode and thus facilitate a more exact study of reservoir problems, even within relatively thin bodies.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Geophysical Research Corp., the Amerada Petroleum Corp., and the Halliburton Oil Well Cementing Co. for permission to publish this paper.

APPENDIX — POTENTIAL THEORY OF GUARD ELECTRODE

In Fig. 11 is given a prolate spheroid in cylindrical coordinates. This figure closely approximates a cylinder which is used as a resistivity well logging electrode. The entire prolate spheroid is maintained at a potential V_e. The current I_e, flowing from the section between b and $-b$, is metered and the ratio $\frac{V_e}{I_e}$ or $\frac{I_e}{V_e}$ is recorded on a scale reading in resistivity or conductivity.

The equation for the surface of the electrode or the prolate spheroid is:

$$\frac{z^2}{c^2}+\frac{r^2}{a^2}=1$$

and the equation for the family of equipotential surfaces out from the electrode is:

$$\frac{z^2}{c^2+\lambda}+\frac{r^2}{a^2+\lambda}=1$$

where $\lambda>0$.

The potential of the equipotential surfaces is given by either Bateman[3] or Smythe[4] as:

$$V=\frac{Q}{2}\int_{\lambda}^{\infty}\frac{du}{(a^2+u)\ (c^2+u)^{1/2}}$$

and is integrated by Bateman:

$$V=\frac{Q}{2k}\ ln\ \frac{\sqrt{c^2+\lambda}+k}{\sqrt{c^2+\lambda}-k}$$

where $k^2=c^2-a^2$, and on substituting $Q=\frac{\rho I}{4\pi}$, we have

$$V=\frac{\rho I}{8\pi k}\ ln\ \frac{\sqrt{c^2+\lambda}+k}{\sqrt{c^2+\lambda}-k}$$

With $\lambda=0$, we have the potential of the electrode:

$$V_e=\frac{\rho I}{8\pi k}ln\frac{c+k}{c-k}$$

$$V_e=\frac{\rho I}{4\pi k}ln\frac{c+k}{a}$$

the electrode resistance:

$$R_e=\frac{\rho}{4\pi k}ln\frac{c+k}{a}$$

and the electrode current:

$$I=\frac{4\pi k V_e}{\rho\ ln\dfrac{c+k}{a}}$$

The surfaces of flow are hyperboloids. The equation is:

$$\frac{z^2}{c^2+\lambda}+\frac{r^2}{a^2+\lambda}=1$$

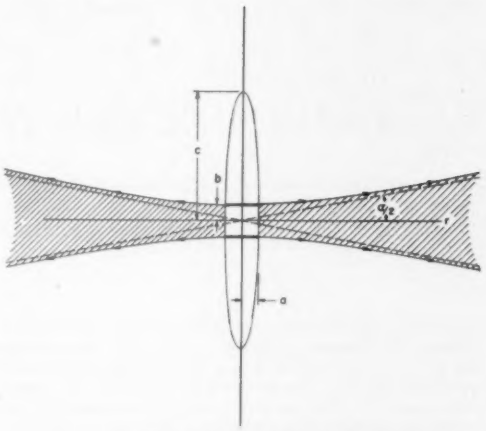


FIG. 11 — GUARD ELECTRODE.

where $-c^2<\lambda<-a^2$. The equation of the hyperboloid that intercepts the z axis at b, *i.e.*, $r=0$ and $z=b$, is arrived at:

$$\lambda=b^2-c^2$$

$$\frac{z^2}{b^2}+\frac{r^2}{a^2+b^2-c^2}=1$$

$$z=b\sqrt{1+\frac{r^2}{c^2-a^2-b^2}}$$

The slope of the flow surface is $\frac{dz}{dr}$. Differentiating, we have:

$$\frac{dz}{dr}=\frac{br}{[(c^2-a^2-b^2)^2+(c^2-a^2-b^2)r^2]^{1/2}}$$

The slope that the flow surface approaches as r increases without limit is:

$$\lim_{r\to\infty}\frac{dz}{dr}=\frac{b}{\sqrt{c^2-a^2-b^2}}$$

The cone that the hyperboloid approaches as r increases, shown in Fig. 11, makes an angle $\frac{\alpha}{2}$ with the r plane. Angle $\frac{\alpha}{2}$ is:

$$\frac{\alpha}{2}=tan^{-1}\left.\frac{dz}{dr}\right]_{r\to\infty}$$

$$\frac{\alpha}{2}=tan^{-1}\frac{b}{\sqrt{c^2-a^2-b^2}}$$

The area of the sphere of infinite radius r_∞ within the angle α is:

$$A_\alpha=4\pi r_\infty^2\int_0^{\frac{\alpha}{2}}2\cos\theta\,d\theta$$

$$A_\alpha=4\pi r_\infty^2\sin\frac{\alpha}{2}$$

and the ratio of this area to the total area is:

$$\frac{A_\alpha}{A}=\sin\frac{\alpha}{2}$$

or the ratio of the current within angle α to the total current is:

$$\frac{I_\alpha}{I} = \sin\frac{\alpha}{2}$$

$$\frac{I_\alpha}{I} = \frac{b}{k}$$

Going back to the equation for V_e and substituting for I, we have:

$$V_e = \frac{\rho I_\alpha}{4\pi b} ln \frac{c+k}{a}$$

and the resistivity is:

$$\rho = \frac{4\pi b}{ln\dfrac{c+k}{a}} \cdot \frac{V_e}{I_\alpha}$$

In order to evaluate the effect of bore hole or mud invasion on the guard electrode, it is desirable to solve the potential problem of a conductive prolate spheroid within one or more cylindrical interfaces, the first interface being bore hole mud to filter cake, etc. However, if the length of the guard electrode is large compared to the diameter of the tool, the length of the measuring ring, the diameter of the bore hole, or the diameter of the invaded zone, a close approximation may be had by bounding the bore hole mud within a second prolate spheroid of minor diameter equal to the bore hole diameter, the invaded zone within a third prolate spheroid, etc.

Let the surface of the guard electrode be a prolate spheroid surface S_1 of major diameter $2\ c_1$ and minor diameter of $2\ a_1$; the next surface S_2 of major and minor diameters of $2\ c_2$ and $2\ a_2$, etc. The equation for the family of equipotential prolate spheroid surfaces is:

$$\frac{z^2}{c_1^2+\lambda} + \frac{r^2}{a_1^2+\lambda} = 1$$

where $\lambda > 0$. The equation of the surface S_a of minor diameter $2\ a_a$ follows:

At the point $z = 0,\ r = a_a$

$$a_a^2 = a_1^2 + \lambda$$

$$\lambda = a_a^2 - a_1^2$$

And the equation:

$$\frac{z^2}{c_1^2 + a_a^2 - a_1^2} + \frac{r^2}{a_a^2} = 1$$

$$\frac{z^2}{a_a^2 + k^2} + \frac{r^2}{a_a^2} = 1$$

At the point $z = c_a,\ r = 0$

$$c_a^2 = a_a^2 + k^2$$

$$c_a = \sqrt{a_a^2 + k^2}$$

Consider:

$$\frac{V_e}{I_\alpha} = \frac{\rho}{4\pi b} ln \frac{c_1+k}{a_1} = R_a \Big]_{s_1}^{\infty}$$

and

$$R_1 = R_a \Big]_{s_1}^{s_2}, \quad R_2 = R_a \Big]_{s_2}^{s_3}, \text{ etc.}$$

For a formation of ρ_t, and a bore of ρ_m, we have:

$$R_2 = R_a \Big]_{s_2}^{\infty} = \frac{\rho}{4\pi b} ln \frac{c_2+k}{a_2}$$

$$R_1 = R_a \Big]_{s_1}^{\infty} - R_a \Big]_{s_2}^{\infty} = \frac{\rho}{4\pi b}\left[ln\frac{c_1+k}{a_1} - ln\frac{c_2+k}{a_2}\right]$$

and the apparent resistivity is:

$$\rho_A = \frac{4\pi b}{ln\dfrac{c_1+k}{a_1}}\left\{ R_1\Big]_{\rho=\rho_m} + R_2\Big]_{\rho=\rho_t}\right\}$$

$$\rho_A = \rho_m + (\rho_t - \rho_m)\frac{ln\dfrac{c_2+k}{a_2}}{ln\dfrac{c_1+k}{a_1}}$$

or:

$$\frac{\rho_A}{\rho_m} = 1 + \left(\frac{\rho_t}{\rho_m} - 1\right)\frac{ln\dfrac{c_2+k}{a_2}}{ln\dfrac{c_1+k}{a_1}}$$

For a formation of ρ_t, and invaded zone of ρ_i, and a bore hole of ρ_m, we have:

$$R_3 = R_a \Big]_{s_3}^{\infty} = \frac{\rho}{4\pi b} ln \frac{c_3+k}{a_3}$$

$$R_2 = R_a \Big]_{s_2}^{\infty} - R_a \Big]_{s_3}^{\infty} = \frac{\rho}{4\pi b}\left[ln\frac{c_2+k}{a_2} - ln\frac{c_3+k}{a_3}\right]$$

$$R_1 = R_a \Big]_{s_1}^{\infty} - R_a \Big]_{s_2}^{\infty} = \frac{\rho}{4\pi b}\left[ln\frac{c_1+k}{a_1} - ln\frac{c_2+k}{a_2}\right]$$

and the apparent resistivity is:

$$\rho_A = \frac{4\pi b}{ln\dfrac{c_1+k}{a_1}}\left\{ R_1\Big]_{\rho=\rho_m} + R_2\Big]_{\rho=\rho_i} + R_3\Big]_{\rho=\rho_t}\right\}$$

$$\rho_A = \rho_m + (\rho_i - \rho_m)\frac{ln\dfrac{c_2+k}{a_2}}{ln\dfrac{c_1+k}{a_1}} + (\rho_t - \rho_i)\frac{ln\dfrac{c_3+k}{a_3}}{ln\dfrac{c_1+k}{a_1}}$$

or:

$$\frac{\rho_A}{\rho_m} = 1 + \left(\frac{\rho_i}{\rho_m} - 1\right)\frac{ln\dfrac{c_2+k}{a_2}}{ln\dfrac{c_1+k}{a_1}} + \left(\frac{\rho_t}{\rho_m} - \frac{\rho_i}{\rho_m}\right)\frac{ln\dfrac{c_3+k}{a_3}}{ln\dfrac{c_1+k}{a_1}}$$

This procedure can be followed for any number of surfaces provided $a_a << c_1$.

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RESULTS OF GAS INJECTION IN THE CEDAR LAKE FIELD

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ABSTRACT

The various factors considered in recommending the initiation of a gas injection project in the southern portion of the Cedar Lake Field are discussed. Performance history under gas injection operations is reviewed and these data are analyzed, utilizing both the material balance method and the fractional flow and frontal advance expressions.

Results of the analysis of the performance data indicate that the injected gas has contacted and affected at least 60 per cent of the reservoir and a substantial increase in ultimate recovery can reasonably be expected. By holding the reservoir pressure appreciably above the bubble point, the well productive capacities have been maintained substantially above the level predicted for primary operations.

The analysis of the Cedar Lake project suggests that in certain limestone reservoirs, at least, the probable success of gas injection cannot be predicted simply from observation of permeability distribution throughout the pay section, as indicated by core analysis data, on either one or a number of wells. Further, the performance of this particular project fails to indicate any basis for classifying carbonate reservoirs in general as being inherently unsuited to a dispersed type gas injection program, thus indicating that each reservoir should be considered on its own merits, regardless of the composition of the reservoir rock.

INTRODUCTION

Early in the life of the Cedar Lake Field, an extensive data gathering program was initiated to provide an accurate record of reservoir performance characteristics. From the study of these data it was apparent that there was a critical need for supplementing the natural reservoir energy in order to maintain well productivities and obtain the maximum ultimate oil recovery. Accordingly, detailed engineering studies were made of the various methods of secondary recovery which might be applicable. As a result of these investigations, the decision was made to initiate a gas injection program of sufficient intensity to maintain reservoir pressure at approximately 600 psia, or some 274 lb above the bubble point pressure of 326 psia.

Manuscript received in the office of the Petroleum Branch, AIME, Sept. 17, 1951. Paper presented at the Petroleum Branch Fall Meeting in Oklahoma City, Okla., Oct. 3-5, 1951.

A full scale dispersed type gas injection program has been in operation on leases of the Stanolind Oil and Gas Co. in the southern portion of the field for nearly five years, and sufficient performance data are now available to evaluate the benefits which have been derived from this project. It is the primary purpose of this paper to analyze the performance data for the Cedar Lake gas injection project and to point out the significance of the observed behavior with respect to certain hypotheses which have been advanced in recent years concerning the probable success of gas injection projects in limestone reservoirs.

This paper properly should be regarded more on the order of a progress report, inasmuch as some revision in interpretation will undoubtedly be required from time to time as additional performance data are obtained, although the satisfactory performance of the project to date leaves little doubt as to the ultimate success of gas injection in the Cedar Lake Field.

As a result of the success of the project to date, a unit was formed in the southern part of the field, effective March 1, 1951, for the purpose of continuation of the gas injection program. Participants in this unit are the Mid-Continent Petroleum Co. and Stanolind Oil and Gas Co.

GEOLOGY AND STRATIGRAPHY

The Cedar Lake Field is located in the northern portion of the Midland Basin area as shown in Fig. 1. The southwest portion of the field lies within a playa, or dry salt lake, which covers an area of approximately eight square miles. As might be expected, it was this lake which furnished the inspiration for the name of the field. Except for its value as a salt water disposal pit, this lake has succeeded only in magnifying the difficulties in developing this portion of the field. Typical of this section of West Texas, the area in general is relatively flat and has a semi-arid climate.

The localized structure which favored the accumulation of oil is an anticline with approximately 100 ft of closure. The major axis of the structure extends in a general southeast-northwest direction. Originally this structure was defined by seismograph data, which have been subsequently confirmed by development.

In general, the geologic column is typical of that found throughout the basin. From the surface to depth of approximately 1,800 ft, surface sands and undifferentiated red beds, probably Triassic, are encountered. Below this point to the producing horizon, all formations are of the Permian age.

FIG. 1 — MAP SHOWING LOCATION OF CEDAR LAKE FIELD.

CHARACTERISTICS OF PRODUCING FORMATION

As a forerunner to that portion of the paper dealing with the actual analysis of the reservoir behavior under gas injection, a discussion of the characteristics of the producing formation appears to be in order, for without a clear understanding of the petrophysics of the reservoir rock, it is difficult to realize the full significance of the behavior of the gas injection program. While examination of cores, radioactivity and electric logs and various other well completion data cannot be expected to provide a definite answer relative to the degree of success to be expected from conducting a gas injection program, these various sources of information must, nevertheless, be given due consideration if an intelligent interpretation is eventually to be made of the performance data and if experience gained from one project is to be of any value in predicting the susceptibility of other reservoirs to gas injection. Accordingly, certain rock characteristics, as observed from log studies and core analysis data, are discussed herein.

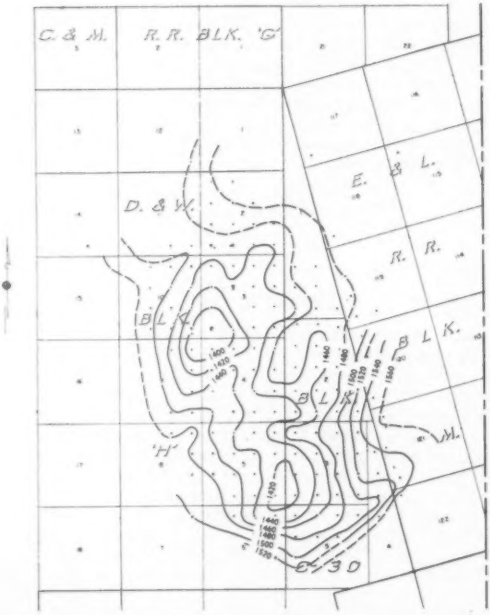
A radioactivity log through the producing section and core analysis data from a typical well in the Cedar Lake Field are shown in Fig. 3. It may be seen that porosity values from the core graph agree reasonably well with the neutron curve of the radioactivity log, a correlation which is demonstrated even more clearly in Fig. 4 where deflections of the neutron curve, measured to the right of the instrument zero line, are plotted against large core analysis porosity values. Such a correlation has proved useful in qualitatively evaluating logs in the gas injection area even though instrument zero values are not available on older logs, the majority of which were obtained

Anhydrite and red beds are found at approximately 2,000 ft and continue with varying amounts of salt, principally sodium chloride, to approximately 2,700 ft where the Cloudchief is encountered. This latter point usually represents the base of the salt section and denotes the appearance of the first limestone stringers.

The Yates horizon, consisting of sand, anhydrite, red beds and lime is found at 2,800 ft. The Yates section grades downward into an anhydrite and red bed series at approximately 3,750 ft where an increase in limestone and sand denotes the top of the Brown lime. A second limestone with considerable anhydrite inclusion is found at 4,000 ft.

The San Andres limestone is encountered at approximately 4,350 ft with the producing horizon usually occurring 4,350 ft with the producing horizon usually occurring from 4,600 ft to 4,700 ft. Although this formation is referred to as a limestone, it actually is a light gray crystalline dolomite with relatively minor anhydrite inclusions. The top of the San Andres and the top of the pay interval are separated by a thin chert streak and a thin sand bed. In the Cedar Lake Field this latter sand is generally referred to as an "intra-dolomite sand break" although in the general area it is more commonly referred to as the Lovington Sand.

The top of the pay occurs in a rather erratic fashion and is not considered to be representative for depicting structural conditions. Because of its uniformity throughout the field and because of its proximity to the producing horizon, however, the intra-dolomite sand break is generally accepted as the most suitable basis for structural delineation. Utilizing this sand as a marker, a structure map has been prepared as shown in Fig. 2. These contours on top of the sand break delineate the anticlinal structure quite clearly.



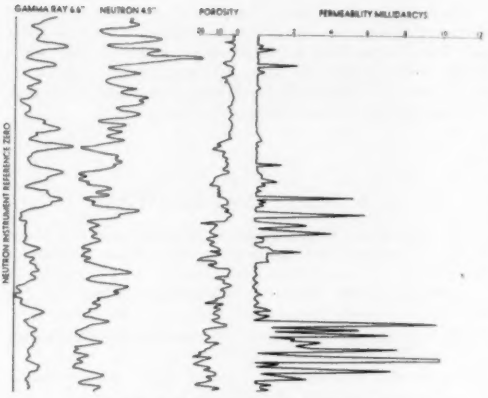


FIG. 3 — TYPICAL CEDAR LAKE WELL LOG.

several years ago. This correlation will prove useful in interpreting pay characteristics in new development areas and in analyzing reservoir behavior, particularly if the injection program is later expanded to include the entire field.

Simply from examination of the permeability profile shown in Fig. 3 and realizing that injection wells were either acidized or shot, it might be concluded that injection into the formation without attempting to control the point of entry would result in the injected gas being confined to an interval of high permeability with the result that a relatively low percentage of the reservoir would be contacted. Elkins and Cook,[1] in observing the behavior of certain pilot gas injection projects, concluded that the part of the reservoir which can be effectively swept by injected gas is a function of permeability profile. While the susceptibility of the reservoir to injected gas must necessarily be dependent on some average condition which exists within the reservoir between the injection and producing wells, it would appear that in limestones and dolomites, at least, this is a condition which cannot be evaluated from observation of core analysis data from one well or several wells, but will necessarily depend on analysis of a well planned and properly controlled injection program.

Referring to Fig. 5, which is a coregraph cross section for four offsetting wells in the Cedar Lake Field, it will be noted that erratic permeability development is encountered in each well; however, closer inspection reveals that intervals of high permeability development cannot be correlated from one well to another. The existence of this condition led to the tentative conclusion by Keller and Morse[2] that vertical variation in permeability, as indicated by core data on individual wells, would be greatly minimized on a reservoir-wide basis to the extent that the flow of injected gas through the formation would be fairly evenly distributed throughout the producing zone. As subsequent discussion will indicate, the validity of this observation seemingly is borne out by the analysis of the performance data.

While most investigators who have studied the physical characteristics of carbonate rocks and sandstones agree that these two types of rock have little in common from the standpoint of pore space geometry, wide differences of opinion apparently exist as to the significance of these lithological dissimilarities. For example, Bulnes and Fitting[3] felt that these observed dissimilarities necessarily would result in reservoir behavior in limestones and dolomites which would differ to a marked extent from the performance observed for sandstones. They believed, for example, that in many limestone fields a large percentage of the oil would be contained in and produced from thick zones having an extremely low order of permeability development and that the rate at which these tight sections produced into more permeable zones would depend in part upon the pressure gradient across the boundary between the two. Since any type of pressure maintenance program would have the effect of minimizing this gradient, it was felt that secondary recovery operations should not be applied indiscriminantly.

Subsequent studies[4,5] of field performance data seemingly have indicated no fundamental differences in the behavior of limestone and sandstone reservoirs, and, as will be shown later in the case of the Cedar Lake reservoir, it has been possible to contact a reasonably large percentage of the reservoir with injected gas. Furthermore it would appear that failure to affect all of the reservoir by injected gas is not attributable to any lithological condition peculiar to carbonate reservoirs but is due simply to formation characteristics which may be found in any reservoir whether it be limestone or sandstone.

In analyzing the behavior of the Cedar Lake injection project, it has been necessary to make use of a relative permeability-liquid saturation relationship derived from the performance of the Slaughter Field[6] where production is also obtained from

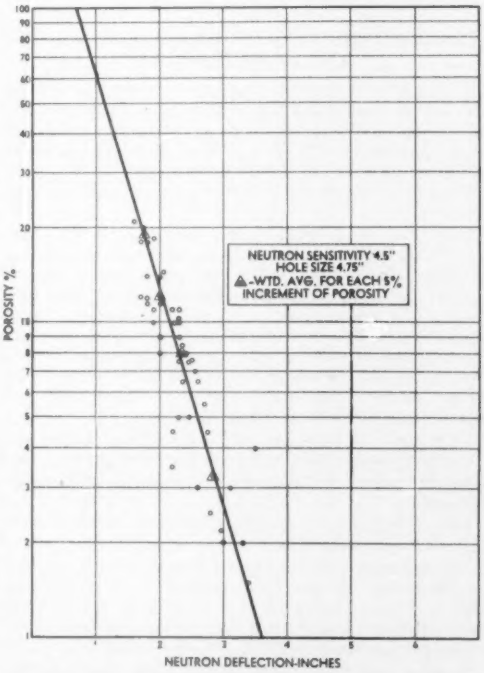


FIG. 4 — NEUTRON DEFLECTION *VS* LARGE CORE ANALYSIS POROSITY.

[1]References given at the end of the paper.

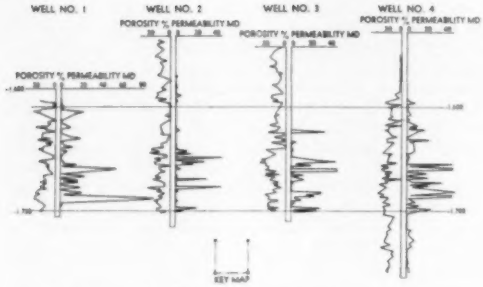


FIG. 5 — CORE GRAPH CROSS-SECTION, CEDAR LAKE FIELD.

the San Andres formation. Use of the Slaughter data is at least partially justified by the fact that a permeability-porosity relationship obtained from a plot of the available core data for the Cedar Lake Field agrees reasonably well with permeability-porosity relationships for San Andres reservoirs located in the North Basin platform area. The relationship for the Cedar Lake Field is shown in Fig. 6. While there is some indication that the San Andres in the Cedar Lake area contains a slightly higher concentration of clayey material than fields in the North Basin area, it nevertheless, occupies roughly the same position on the graph as core data from the Slaughter and Wasson Fields.

CHARACTERISTICS OF RESERVOIR FLUID AND INJECTED GAS

In order to evaluate the reservoir fluid characteristics, a number of representative bottom hole samples have been obtained from various portions of the field. These data indicated close agreement and were combined to provide composite curves as shown in Fig. 7. No significant difference in crude characteristics in different portions of this structure has been detected.

From a review of these composite data, it is readily apparent that the reservoir crude is highly undersaturated, having a bubble point pressure of 326 psia and a solution gas/oil ratio of 156 cu ft/bbl. Original reservoir pressure was indicated to be approximately 1,950 psia. Oil viscosity varies from a value of 2.90 cp at original reservoir conditions to 2.44 cp at the bubble point pressure, at which point the viscosity increases rapidly to 4.5 cp at atmospheric conditions. The relative volume of this crude is 1.0768 at original conditions and increases to 1.0884 at the bubble point.

As pointed out previously, the undersaturated nature and low solution ratio of this crude were important factors in dictating the necessity for the initiation of a pressure maintenance program.

Laboratory fractional analysis of the reservoir oil is given in Table I of the appendix.

Although most of the gas injected to date has been obtained from the nearby Homann Field, attempts are currently being made to develop a source of gas from the Yates Sand horizon within the Cedar Lake Field itself. Fractional analyses of the two gases are given in Table II of the appendix.

Shown in Fig. 8 are compressibility factor curves for the above two gases. As a result of its higher nitrogen content, the Cedar Lake Yates sample is, of course, less compressible and has a higher viscosity. These characteristics have a decided advantage in providing for future make up gas volumes since lower compressibility of this gas would reduce injection requirements by approximately three per cent and the higher viscosity makes it a more efficient displacing fluid.

GAS INJECTION FACILITIES

The Homann Field gas, which is produced from the Yates horizon, is metered and delivered at a maximum pressure of 450 psig to the Stanolind transmission line at its terminus in the Homann Field. Due to resultant lines losses, the gas reaches Stanolind's compressor station at about 325 psig. Being relatively dry and sweet, this gas does not require special treatment prior to entering the compressors.

Compression from an intake pressure of 325 psig to a maximum discharge pressure of 1,600 psig is accomplished in two stages. Following compression, the gas is transmitted to the individual injection wells by injection lines as shown on Fig. 9. Each injection well is equipped with an adjustable choke and adequate valves to permit flexibility in control of the individual wells, and a differential, mercury-type orifice flow meter is provided for measurement of gas injected into each well. The accumulation and freezing of hydrates is minimized through the use of a methanol injector at the plant, and the

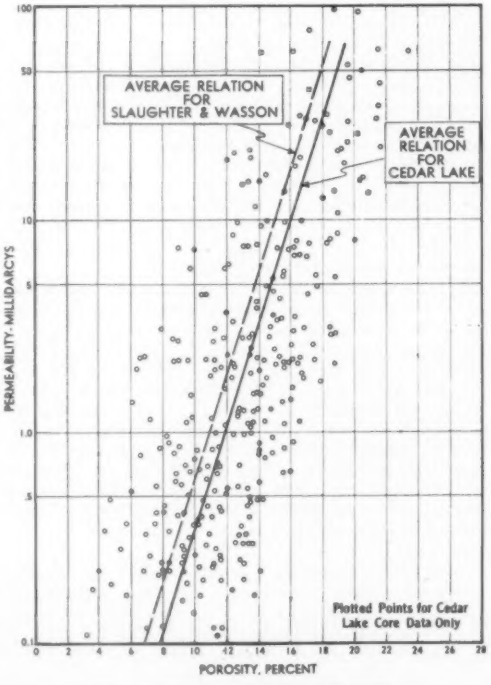

AVERAGE RELATION FOR SLAUGHTER & WASSON
AVERAGE RELATION FOR CEDAR LAKE
Plotted Points for Cedar Lake Core Data Only
PERMEABILITY-MILLIDARCYS
POROSITY, PERCENT

FIG. 6 — POROSITY-PERMEABILITY RELATION.

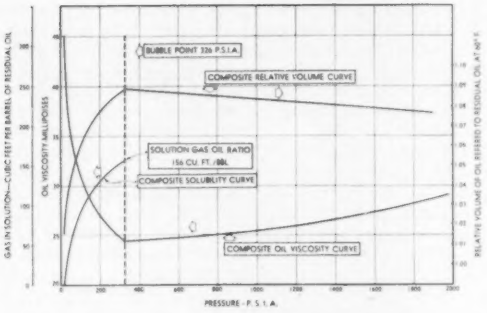

BUBBLE POINT 326 P.S.I.A.
COMPOSITE RELATIVE VOLUME CURVE
SOLUTION GAS OIL RATIO
156 CU. FT./BBL.
COMPOSITE SOLUBILITY CURVE
COMPOSITE OIL VISCOSITY CURVE
PRESSURE - P. S. I. A.

FIG. 7 — CEDAR LAKE FIELD RESERVOIR CRUDE CHARACTERISTICS.

freezing of injection wellhead equipment due to the high degree of expansion across adjustable chokes is controlled by heating the gas in small gas-fired heaters placed a short distance from the individual wellheads.

Gas obtained from the Yates horizon in the Cedar Lake Field is high pressure gas and requires no compression for injection. Connections from the two Yates sand gas wells to the injection system are shown in Fig. 9.

HISTORY AND PAST PERFORMANCE

Following detailed seismic work, Stanolind drilled and completed its J. B. Rayner No. 1, the discovery well for the field, in August, 1939. Development of the field progressed rather slowly during the first few years of the field's history and was essentially halted during the period from 1943 to 1948. An intensified drilling program undertaken since that time, however, has resulted in an extension of field limits a considerable distance to the north and virtually doubled the previously indicated productive acreage. Although the field limits have now been reasonably well defined in the southern half of the field, drilling activity continues at a somewhat lessened pace in the northern portion of the field.

Performance of the injection area prior to initiation of this secondary program is illustrated in Fig. 10. Of particular importance is the rapid decline in bottom hole pressure which occurred during this period when production from the reservoir was attributable only to the energy expended by expansion of the reservoir liquid. In consideration of the relatively low permeability and the attendant high abandonment pressures of the major portion of this reservoir, indications were that under primary operations the field could reasonably be expected to recover not more than 10 to 12 per cent of the oil initially in place. Individual well productivity would, of course, be appreciably reduced when the reservoir pressure declined below the bubble point. During this phase of operations, the presence of liberated solution gas in the reservoir would materially reduce the effective permeability to oil and there would be only a small pressure differential available to move oil to the well bore.

Gas/oil ratio behavior during this period of primary operations was consistent with that expected from bottom hole sample analysis which indicated a solution ratio of 156 cu ft/bbl. Oil production, as shown in Fig. 10 varied over a rather wide range with fluctuations attributable principally to rate of development, early proration practices, and greatly accelerated demand during the war years.

Recognizing the extremely low efficiency of primary operations, gas injection operations were initiated in April, 1946, in one well. Injectivity and fluid depression tests were conducted on the proposed injection wells, and the results indicated that the volumes required to maintain pressure could be achieved at an injection pressure of approximately 1,100 psig. By November of 1946, the number of injection wells had been increased to eight, with a ninth well being added in October, 1948. This amounts to a density of over 250 acres per injection well. At the time the program was initiated the reservoir pressure had declined to approximately 600 psia and original plans were designed to maintain pressure at that level.

A study of Fig. 10 reveals appreciable fluctuation in injection volumes during the early stages of this operation. Since this project essentially represented an experiment as well as a practical application of the principle of gas injection in limestone reservoirs, such variations might be expected during the initial stages. An almost immediate effect on the bottom hole pressure was noted, however, and as injection volumes increased to the point where they exceeded withdrawals, there was a rather significant increase in reservoir pressure. Subsequently, however, injection volumes were readjusted to a value more nearly approaching reservoir withdrawals, and the recorded bottom hole pressure reflected a decline in pressure to the desired value of approximately 600 psia. Continued close supervision of the project is expected to effect a satisfactory balance between withdrawals and injection volumes and to assure maintenance of the reservoir pressure at the desired point. Certainly the program to date has resulted in a very significant alteration of the original trend of pressure observed under primary conditions.

Associated with retardation of pressure decline, we might logically expect a similar arresting of the decline in individual well productivity. Original productivity indices of these wells were in the range of 0.05 to 0.2 B/D per pound drawn down in bottom hole pressure. These PI values, of course, are a further indication of the low order of permeability and furnish additional confirmation of the need for pressure maintenance. Current well productivity is indicated to average ap-

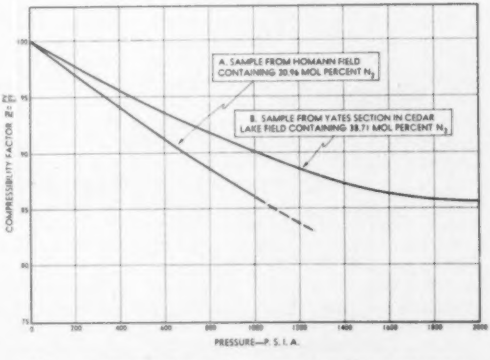

A. SAMPLE FROM HOMANN FIELD CONTAINING 30.96 MOL PERCENT N_2
B. SAMPLE FROM YATES SECTION IN CEDAR LAKE FIELD CONTAINING 39.71 MOL PERCENT N_2
COMPRESSIBILITY FACTOR Z = PV/RT
PRESSURE—P. S. I. A.

FIG. 8 — COMPRESSIBILITY OF INJECTED GAS, CEDAR LAKE FIELD.

proximately 68 B/D per well, whereas it is estimated that at the present time under primary operation the average well would be capable of producing only 44 B/D.

Since gas injection was initiated at a reservoir pressure well above the bubble point, there was no significant increase in the produced gas/oil ratio during the first 19 to 20 months of the injection program. Gas breakthrough was first detected in the middle of 1948 and a series of produced gas samples were collected and analyzed to confirm the fact that injected gas was being produced.

During this five-year period of injection, actual production has been approximately 400,000 bbl greater than the estimated production under primary operation. This increased production represents the benefits received to date from the standpoint of maintaining well productivity.

In general, it is apparent, before even attempting a quantitative evaluation of the performance data, that the behavior of this project to date is indicative of a high degree of success in maintaining reservoir pressure and productive capacity and holds promise of considerable increase in ultimate recovery. In reviewing the various factors affecting the success of this program, we believe that it should be pointed out that one of the most important considerations is the initiation of an adequate data gathering program to permit an intelligent appraisal of the performance of the project and the adoption of a sufficiently flexible plan of operations to permit necessary alterations in the injection program as dictated by the observed performance.

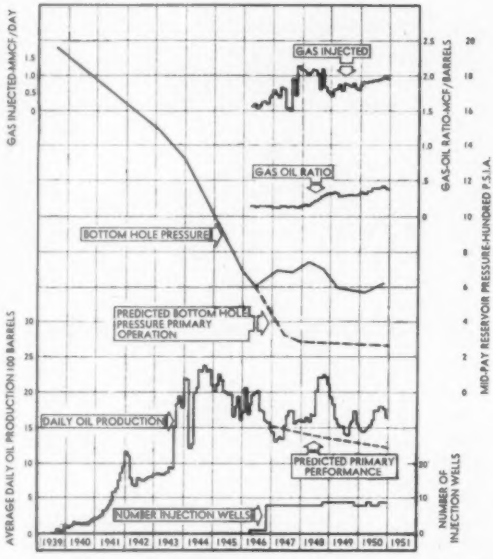

GAS INJECTED-MMCF/DAY
GAS-OIL RATIO-MCF/BARRELS
MID-PAY RESERVOIR PRESSURE-HUNDRED P.S.I.A.
AVERAGE DAILY OIL PRODUCTION-100 BARRELS
NUMBER OF INJECTION WELLS
GAS INJECTED
GAS OIL RATIO
BOTTOM HOLE PRESSURE
PREDICTED BOTTOM HOLE PRESSURE PRIMARY OPERATION
DAILY OIL PRODUCTION
PREDICTED PRIMARY PERFORMANCE
NUMBER INJECTION WELLS
1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951

FIG. 10 — PERFORMANCE HISTORY, CEDAR LAKE GAS INJECTION AREA.

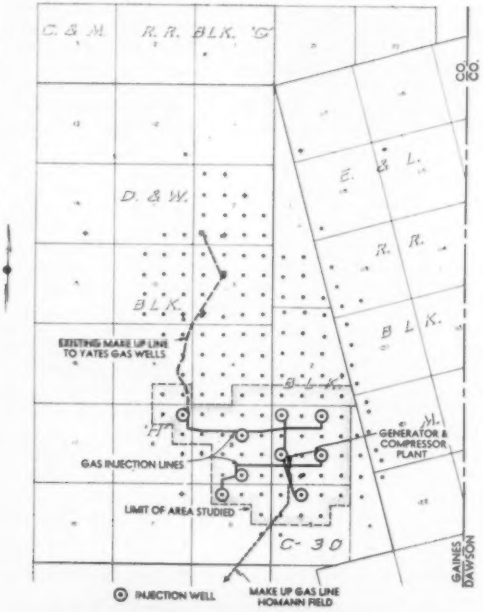


FIG. 9 — INJECTION FACILITIES, CEDAR LAKE FIELD.

ANALYSIS OF RESERVOIR PERFORMANCE

As pointed out previously, full scale gas injection operations had been in progress for a period of approximately 19 to 20 months before any increase in the produced gas/oil ratio was detected. The injection of gas over an extended period of time without any noticeable increase in the ratio was, of course, encouraging in that it provided a qualitative measure of the success of the injection program. At the same time, however, it necessarily delayed any attempt to evaluate quantitatively the performance data.

In analyzing the performance history of a gas injection program in which the pressure is maintained above the bubble point, two avenues of approach are open to the solution of the problem: (1) the material balance method and, (2) the application of the fractional flow and frontal advance expressions. The former, in its conventional form, does not take into consideration the time required for gas breakthrough, whereas the latter method is inherently suited to that particular phase of the gas injection program. It follows then that an attempt to interpret the results of the Cedar Lake injection program properly should utilize both methods of analysis.

Material Balance Method

The material balance method for predicting the behavior of gas drive reservoirs under both primary and gas injection operations has been adequately discussed in the literature[6,7] and will not be repeated at this time. By way of proper introduction to certain material to be presented later, however, it may be well to review briefly the use of the term "conform-

ance factor." This term is generally defined as representing that fractional part of the reservoir contacted and affected by injected gas. This assumes, of course, that the remainder of the formation continues to perform as a simple depletion type reservoir. Modification of the material balance equation to include a conformance factor has been discussed in some detail by Patton[6] and by Pirson.[8]

In predicting the performance of any reservoir under gas injection operation, the most significant unknown is the portion of the total reservoir that will be affected by the injected gas. This factor will, of course, be different for different fields due to the fact that the permeability profile and structural and lithological conditions will vary from one reservoir to another.

The evaluation of the Cedar Lake project makes use of the material balance method to calculate theoretical gas/oil ratio trends assuming various conformance factors. These calculated trends are compared with the gas/oil ratio behavior actually observed in the injection area to determine what fraction of the pay has been affected in this project.

Mention was made previously of the lithological similarities between the Cedar Lake Field of the Midland Basin area and the San Andres reservoirs of the North Basin Platform area. While the order of permeability development is somewhat lower in the Cedar Lake Field than in the Slaughter Reservoir, previously discussed similarities in rock characteristics suggest that a relative permeability-liquid saturation relationship based on performance of certain areas in the Slaughter Field[5] should be applicable to the Cedar Lake reservoir.

Fortunately, considerable core analyses are available in the Cedar Lake Field and these data together with information from radioactivity and electric logs provide a reasonably accurate indication of the volume of oil initially contained in that portion of the reservoir underlying the injection area. This figure together with the Slaughter Field relative permeability relationship provides the basic information required to undertake an analysis of the performance history for the Cedar Lake Injection Project.

Utilizing the Slaughter relative permeability data and Cedar Lake crude characteristics, a number of "apparent" relative permeability-liquid saturation trends have been calculated assuming various conformance factors. These data extend over a conformance factor range of 40 to 100 per cent as shown in Fig. 11. The curve for a conformance factor of 100 per cent, of course, represents the trend actually calculated from Slaughter Field performance data and occupies a position on the graph which might reasonably be expected from analysis of the Cedar Lake Injection project if all of the reservoir underlying the injection area were contacted and affected by injected gas.

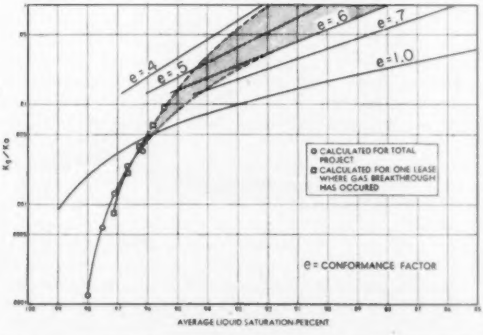


FIG. 11 — RELATIVE PERMEABILITY — LIQUID SATURATION RELATIONS FOR VARIOUS CONFORMANCE FACTORS.

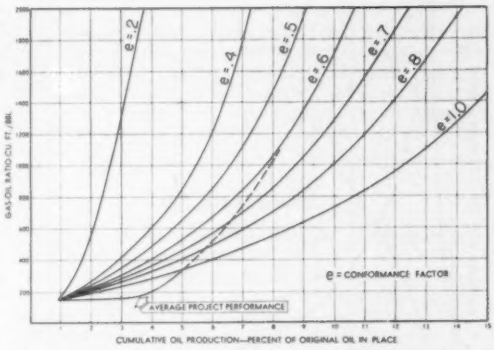


FIG. 12 — GAS/OIL RATIO BEHAVIOR VS CUMULATIVE OIL PRODUCTION FOR VARIOUS CONFORMANCE FACTORS.

Apparent relative permeability trends calculated from the total project performance data and the performance history of a large lease in the area, where gas breakthrough has occurred in the majority of the producing wells, are also shown in Fig. 11. It will be observed that data from the one lease illustrated can reasonably be extrapolated along the trend which would indicate a conformance factor in excess of 40 per cent and the apparent relative permeability trend for the total injection area coincides reasonably well with a conformance factor of 60 per cent.

With regard to the lease performance data shown in Fig. 11, it might be well to mention that the indication of a somewhat less favorable conformance factor is undoubtedly partially attributable to the fact that injection volumes have exceeded withdrawals to a slight degree and that no attempt was made to compensate for this condition in analyzing the performance data. It should be kept in mind that similar situations of an even more extreme nature are frequently observed in pilot projects involving only one or two injection wells, thereby leading to a condition which makes any attempt at a quantitative evaluation extremely difficult. In some instances, failure to recognize the importance of this particular phase of the problem has undoubtedly led to the conclusion that the injected gas had "channeled" and that an injection program on a fieldwide basis would not be economically attractive, whereas proper consideration of all factors involved possibly would not have led to such a conclusion.

Results of the analysis of performance history are shown in a somewhat different manner in Fig. 12, on which is indicated gas/oil ratio trends for conformance factor values ranging from 20 to 100 per cent. As will be noted, the gas/oil ratio behavior for the injection project is practically flat in the early portion of the injection history, occupying a position on the graph well below the theoretical behavior calculated for a reservoir having a conformance factor of 100 per cent. Following gas breakthrough, however, it will be observed that

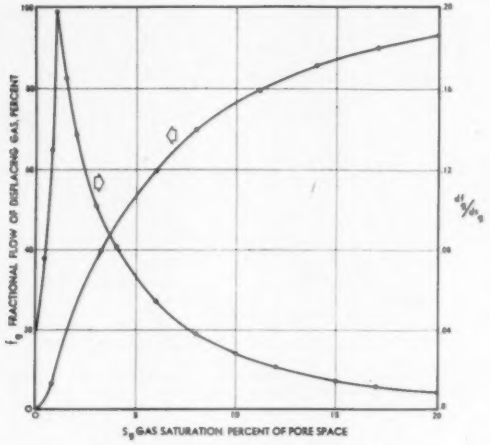


FIG. 13 — f_g AND df_g/ds_g AS FUNCTIONS OF S_g.

the ratio increases along a trend which indicates that a conformance factor of 60 per cent might reasonably be expected.

As mentioned previously, the material balance approach fails to take into account the time required to establish breakthrough of gas where injection is initiated in a reservoir at some pressure above the bubble point and maintained at that level. Utilizing the material balance approach, this results in the calculation of a condition prior to gas breakthrough which is obviously a physical impossibility and which can best be handled through use of the fractional and frontal advance expressions.

Application of Fractional Flow and Frontal Advance Expression

Neglecting the effects of gravity drainage and capillary pressure, the fractional flow formula of Buckley and Leverett may be stated as follows:

$$f_g = \frac{1}{1 + \frac{k_o}{k_g} \cdot \frac{\mu_g}{\mu_o}} \quad \ldots\ldots\ldots\ldots (1)$$

where

f_g = fraction of gas flowing

k_o/k_g = relative permeability ratio of oil to gas

μ_g/μ_o = viscosity ratio of gas to oil

Utilizing the above relation, the fraction of gas flowing (f_g) has been calculated for various values of gas saturation and plotted as shown in Fig. 13. This curve was then differentiated graphically to obtain a plot of df_g/ds_g *vs* gas saturation.

In order to calculate the rate of advance and determine the space position of the front of saturation discontinuity, use has been made of the linear rate of advance equation modified for application to a radial system. This relation is as follows:

$$u = \left(r_w^2 + \frac{2r_w}{\Phi A} Q_t \frac{df_g}{dS_g} \right)^{1/2} - r_w \quad \ldots\ldots (2)$$

where:

r_w = radius of well bore

Φ = porosity

A = area of well bore face in net pay interval

Q_t = total volume of displacing fluid in a unit of time

u = distance from well bore face at which the corresponding saturation exists

Utilizing data which are representative of average injection well conditions, Equation (2) has been solved for an injection period of 300 days using a total injection volume of 32,100 Mcf of gas. The results of this calculation, which are shown in Fig. 14, indicate that the injected gas should advance a distance of 398 ft from the well bore in 300 days. A second calculation was made utilizing the average gas volume injected during one day. Since we are concerned with a radial system in which the relationship between injection days and feet of advance of the front is a straight line relationship on logarithmic graph paper provided the injection rate is constant as shown in Fig. 15, additional calculations were unnecessary. Extrapolation of the relationship established by the two calculated points indicates that the gas front should advance 1,320 ft (the average distance between producing and injection wells) in approximately 1,130 days, if all pay were affected. Had these calculations been made on the assumption that only a fraction of the pay were affected by the injected gas, the time required for the front to reach a given distance would be reduced proportionately. Referring to the gas/oil ratio behavior as shown in Fig. 10, it will be observed that an increase in the ratio occurred approximately 19 to 20 months (578 to 608 days) after the project was expanded to include nine injection wells. From the ratio of the observed to calculated time for gas breakthrough, a conformance factor on the order of 50 to 60 per cent appears to be reasonable.

This procedure for analyzing the performance history is subject to at least one rather severe limitation in that it makes use of a portion of a field derived relative permeability relationship over a range of liquid saturations where the calculated relative permeability values are particularly sensitive to variations in stage of depletion of various portions of the reservoir. In other words, it has been commonly assumed that

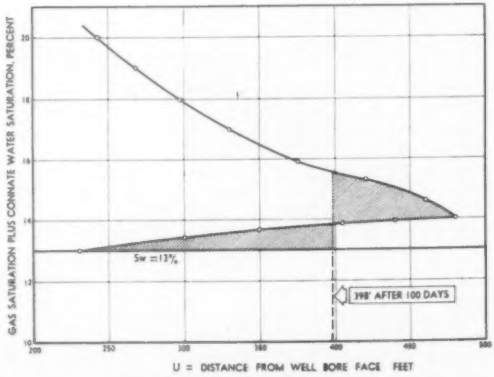


FIG. 14 — CALCULATION OF SATURATION DISTRIBUTION PRIOR TO GAS BREAKTHROUGH.

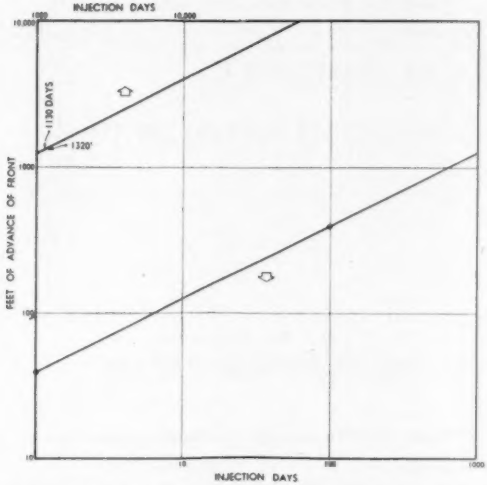


FIG. 13 — INJECTION DAYS VS FEET OF ADVANCE OF FRONT FOR AVERAGE CONDITIONS IN INJECTION AREA, CEDAR LAKE FIELD.

relative permeability trends calculated from field data are pessimistic for high values of liquid saturation due to the increase observed in gas/oil ratio almost immediately in the field's productive history.

In this regard it should be pointed out that the Slaughter Field relative permeability-liquid saturation relationship was calculated from certain selected areas within the field, in which case appreciable spatial variation in liquid saturation appears unlikely. Furthermore, recent laboratory relative permeability work based on internal gas drive experiments has indicated surprisingly good agreement, at high values of liquid saturation, with relationships derived from actual field performance data.[11] For this reason it is felt that there is considerable justification for use of the field derived relative permeability relationship.

FUTURE RESERVOIR BEHAVIOR

As pointed out in the introduction, the primary purpose in presenting this paper was to analyze the available reservoir performance data, however, a statement relative to future behavior of the reservoir would appear to be in order at this time.

Secondary recovery programs are undertaken primarily for the purpose of increasing ultimate recovery and, if the situation demands, maintenance of well productive capacities. In this latter regard, it is apparent from the foregoing discussion that little doubt remains as to ultimate success of the Cedar Lake injection program. Accordingly, it will suffice to say that projection of the observed performance data to depletion, utilizing a conformance factor of 50 per cent, indicates that an appreciable increase over primary recovery can reasonably be expected and, further, that the area under gas injection operation will be depleted in approximately the same length of time as would have been required under primary operation. This is an understandable development when consideration is given to the fact that practically all of the recovery under primary operations would necessarily be obtained after the reservoir pressure had declined to the bubble point of 326 psia, and at this reservoir pressure extremely low pressure differentials would be available for movement of fluid to the well bore.

CONCLUSIONS

In light of the foregoing discussion, the following conclusions appear to be in order:

1. Injection into the oil column in the Cedar Lake Field without attempting to control the point of entry of the gas has resulted in at least 60 per cent of the total reservoir being contacted and affected by the injected gas.
2. Derivation of the "conformance factor" from performance history in the fashion illustrated will permit quantitative evaluation of the ultimate benefits of a dispersed gas injection program, and will permit evaluation of the economics of injection of varying intensity.
3. It would appear that in many limestone reservoirs the probable success of a dispersed type gas injection program cannot be predicted from observation of permeability distribution in either one or a number of wells but necessarily must be determined by conducting a well planned injection program over a sufficiently large area, thereby minimizing the problems frequently associated with the usual pilot type of operation in which only one or two injection wells are involved.
4. The performance of the Cedar Lake gas injection project indicates the absence of any basis for classifying carbonate rocks in general as being inherently unsuited to a dispersed type of gas injection program, thus indicating that each field should be evaluated on its own merits regardless of whether production is obtained from a limestone or a sand.

APPENDIX

The calculation of saturation distribution prior to gas breakthrough, as shown in Fig. 14, makes use of the Buckley and Leverett linear rate of advanced relationship modified for application to a radial system.

For unit volume of a linear system, it has been shown that a material balance expression, relating total influx and efflux of occupying and displacing fluids in the unit volume, may be written as follows:

$$\left(\frac{dS_d}{d\Theta}\right)_u = \frac{q_t}{\Phi A}\left(\frac{df_d}{du}\right)_\Theta \quad \ldots \quad (1)$$

where:

S_d = saturation of displacing fluid
f_d = fractional flow of displacing fluid
q_t = total fluid flow
Φ = porosity
A = area
Θ = time
u = distance

Equation (1) may be reworked mathematically to give:

$$\left(\frac{\partial u}{\partial \Theta}\right)_{S_d} = \frac{q_t}{\Phi A}\left(\frac{\partial f_d}{\partial S_d}\right)_\Theta \quad \ldots \quad (2)$$

which states that the rate of advance of a plane of constant saturation in displacing fluid (S_d) is proportional to the

change in composition of the flowing stream caused by a small change in saturation of the displacing fluid. The "rate of advance" equation, (2), was derived for a linear system, but may be adapted to a radial system by multiplying the expression by the ratio $\frac{r_w}{r_w + u}$, where r_w is the well bore radius and u is the radial distance from the bore face. The expression then becomes, for a radial system:

$$\left(\frac{\partial u}{\partial \Theta}\right)_{S_d} = \frac{q_t}{\Phi A}\left(\frac{\partial f_d}{\partial S_d}\right)_\Theta \left(\frac{r_w}{r_w + u}\right) \quad . \quad (3)$$

This differential equation is then rearranged by separation of variables, integrated, and solved for the distance u, which gives:

$$u = \left(r_w^2 + \frac{2r_w}{\Phi A} Q_t \frac{df_d}{dS_d}\right)^{1/2} - r_w \quad . \quad . \quad (4)$$

where:

r_w = radius of well bore
Φ = porosity
A = area of bore face in net pay interval
Q_t = total volume of displacing fluid in a unit of time
u = distance from bore face at which the corresponding saturation exists as a result of injecting Q_t

Actually the values of u obtained for varying values of $\frac{df_d}{dS_d}$ (*i.e.*, gas saturation), when plotted against total saturation, will represent the saturation distribution behind the advancing front. This may then be interpreted to give the actual rate of advance of the front. Hence, we have an expression which relates the rate of advance of a front to the total volume of displacing fluid. In adapting the Equation (4) to our case, the displacing phase becomes injected gas. ($f_d = f_g$ and $S_d = S_{g'}$)

Table I — Fractional Analysis-Reservoir Oil

Component	Mol. Per Cent
N_2	.39
H_2S	1.05
CO_2	.50
C_1	6.64
C_2	7.78
C_3	9.67
iC_4	1.34
nC_4	5.59
iC_5	2.26
nC_5	2.57
C_6	2.70
C_{7+}	59.51
	100.00

Mol. Wt. $(C_{7+}) = 238$
API Gravity $(C_{7+}) = 29.4°$

Table II — Fractional Analysis-Injection Gas

Component	Mol. Per Cent	
	Homann Field	Cedar Lake Field
N_2	20.96	38.71
CO_2		.10
C_1	63.08	49.61
C_2	9.45	6.60
C_3	4.24	3.07
iC_4	.40	.46
nC_4	1.13	.63
iC_5	.20	.25
nC_5	.28	.38
C_6	.19	.14
C_{7+}	.07	.05
	100.00	100.00
Gravity @ 60°F	.767	.8135
Net BTU Cont. cu ft	885	754

ACKNOWLEDGMENT

The authors wish to express their appreciation to the Stanolind Oil and Gas Co. for permission to publish this paper.

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FURTHER DISCUSSION OF PAPERS PUBLISHED IN TRANSACTIONS, VOLUME 192 (1951)

RELAXATION METHODS APPLIED TO OIL FIELD RESEARCH

H. DYKSTRA AND R. L. PARSONS, CALIFORNIA RESEARCH CORP., LA HABRA, CALIF., MEMBERS AIME

(Published as T.P. 3145, Page 227)

DISCUSSION

By E. C. Larman, Anglo-Iranian Oil Co., Ltd., Kirklington Hall Research Station, England

It is notable that the authors, in their reply to Nowak, state that the application of the procedure described in their paper is not possible to nonsteady state flow. Since such flow is of great importance in oil field research, and since methods do exist for obtaining a solution by relaxation methods, it is desirable that the false impression should be removed.

Allen and Severn[1] have shown that relaxation methods can be applied to nonsteady state problems. In particular they solve, by way of illustration, an equation of the "heat conduction" type, *viz.*:

$$K\frac{\partial^2 v}{\partial x^2} = \frac{\partial v}{\partial t} \quad \ldots\ldots\ldots\ldots (1)$$

which is of interest in oil field research since, in its general form

$$K\triangle^2 p = \frac{\partial p}{\partial t}$$

it is the equation governing compressible fluid flow in porous media.[2]

In order to solve a partial differential equation by relaxation it is necessary that the solution satisfies suitable boundary conditions at all points of a closed boundary and we say that such a problem is of a "jury" type.

By way of illustration we may take the case of an ordinary one dimensional differential equation.

The boundary conditions which must be equal in number to the order of the equation may be given in equal numbers at each end or unequally distributed between the ends — perhaps all at one end. The first is a "jury" problem while the others are "marching" problems.[3] We note at once that an odd order equation cannot be a "jury" problem.

Returning to Equation (1) it is apparent that we could lay down a rectangular net of t against x in a similar manner to that for x and y in the article. We extend the t axis up to the value of interest $t = t_1$ and our difficulty is at once apparent. We cannot lay down the conditions for $t = t_1$ because this is just what we are after. The very nature of the problem implies that, at best, we can only know the boundary conditions on three sides, *viz.*, the distribution along x for $t = 0$, the distribution in t for $x = 0$ and the distribution in t for $x = 1$. The answer required is the distribution in x for $t = t_1$ and if we knew it there would be no problem.

Allen and Severn overcame this difficulty in an ingenious way and in a way which would be quite useless by classical methods. They double the order of the equation. Equation (1) is transformed by making the dependent variable a differential function (suitably chosen) of a new dependent variable. The effect of this is to provide the means of having sufficient disposable extra boundary conditions to convert the problem to "jury" type. The substitution chosen results in an equation of the form:

$$\frac{\partial^2 w}{\partial t^2} - K^2\frac{\partial^4 w}{\partial x^4} = 0 \quad \ldots\ldots\ldots (2)$$

and although this is much more complicated judged by classical standards this is no criterion for a numerical method. The real point at issue is that a nonsteady state problem has been solved by relaxation methods.

It is shown in the paper[3] that the mesh interval in the t direction is not independent of that in the x direction but since we can take the x divisions at will this is no disadvantage. It is also shown that though the finite difference approximation to Equation (2) leads to a more complicated relaxation pattern than for Equation (1) yet for computation that for Equation (2) has a distinct advantage. For a discussion

of the necessity for n boundary conditions to deal with a differential of order $2n$ or $2n-1$, consideration of odd order equations, practical points, choice of transformation, added boundary conditions, and a worked example reference should be made to the original paper.[1]

In addition, attention may be drawn to the fact that Allen and Dennis[4] have shown that a three dimensional problem, *e.g.*

$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} = W\ (x, y, z)$$

can be solved on a sheet of paper (two dimensions) by suitable care in arranging the work.

The writer suggests therefore, that the solution of a "four dimensional" nonsteady state equation, *e.g.*,

$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} = \frac{1}{K}\frac{\partial w}{\partial t}$$

by relaxation is dependent only on a suitable "storage" mechanism and transformation. In its simplest form the "storage" would consist of many sheets of paper each containing a three dimensional aspect. That this would be a highly involved procedure is obvious but the point to be established is that it is the "storage" problem which is the limiting factor, not the method.

It is not necessarily suggested that relaxation is a good way of solving nonsteady state problems, only that it can, and has been done.

Finally attention may be drawn to a paper by C. J. Tranter,[5] who shows that in some cases a three dimensional problem may be reduced to a set of problems in two dimensions.

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AUTHORS' REPLY TO MR. LARMAN

The comments of Larman on our paper "Relaxation Methods Applied to Oil Field Research" are very good. He shows that by suitable transformation a nonsteady state flow problem can be solved by the relaxation principle; we are indebted to Larman for his contribution.

In his concluding comments, Larman suggested that solution by relaxation of nonsteady state problems "would be a highly involved procedure;" and further that even though solution by relaxation be possible, other methods of attack might be better. We agree. In particular, capacitor-resistor network models, such as those developed by V. Paschkis, and later by W. A. Bruce, are designed to handle nonsteady state flow problems. From a practical point of view, anyone attempting to solve a nonsteady state flow problem by relaxation has a job to do; whereas a very similar problem in steady state is simple and quick. ★ ★ ★

THE CALCULATION OF PRESSURE DROP IN THE FLOW OF NATURAL GAS THROUGH PIPE

FRED H. POETTMANN, PHILLIPS PETROLEUM CO., BARTLESVILLE, OKLA., JUNIOR MEMBER AIME

(Published as T.P. 3217, Page 317)

DISCUSSION

By W. C. Mosteller, Southern Counties Gas Co. of California, Los Angeles, Calif.

Poettmann develops by mathematical manipulation of basic equations a means of taking into account the deviation of natural gas from ideal gas behavior. Specific attention is given to:

a. Calculation of pressure loss (or sand surface pressure) of flowing gas wells;
b. Flow of gas in pipe lines;
c. Calculation of isothermal horsepower required to compress natural gas.

I believe the author's flow equation derivation is not mathematically rigorous. This applies to his integration process and treatment of average velocity in Equations (4), (14), (28), (29), (30) and (31). More detailed comment of the author's mathematics is given in Appendix 1 below.

Under some conditions the author's flow equations will give correct results; under others, they will not. For instance, in Poettmann's pipe line example, he computes the flow through a 50-mile 26-in. line with an upstream pressure of 825 psia and a downstream pressure of 565 psia to be 462 MMcf/D. Calculation by a formula derived through rigorous mathematics would, in this case, also give a flow of approximately 462 MMcf/D. If, in this pipe line, however, the upstream pressure had been 825 psia and the downstream pressure 135 psia, the author would have computed a flow rate of 545 MMcf/D; whereas the correctly computed flow rate is 624 MMcf/D (using the author's friction factor in each computation).

W. O. Clinedinst[1] developed a pipe line flow formula along a line of thought similar to that of Poettmann's. Although Clinedinst did not present his material in such a convenient tabular form as Poettmann's Table I, Clinedinst's formula is derived by more exacting mathematics. Later, Joffe[2] extended Clinedinst's work to provide computation charts that are more convenient to read and use. P. MacDonald Biddison[3] developed a simplified procedure for making the deviation correction applicable to pipe lines operating at 2,000 psig or less.

In Poettmann's development of his equation for gas flowing from wells, the kinetic energy factor is eliminated on the as-

sumption that it is negligible. I am of the opinion that the kinetic energy factor would not be negligible in all computations involving flowing gas wells.

In my opinion, Poettmann's Table III, which purports to illustrate the accuracy of his vertical pipe flow equation, is misleading. I believe that the percentage accuracy figures given in the last column of this table are not indicative of the accuracy of his flow formula since these percentages are based upon the total observed pressure and not the relation between the computed pressure drop and the observed pressure drop.

Poettman's formula for isothermal horsepower requirements to compress natural gas is developed in a manner which is mathematically precise. In my opinion, however, actual gas compression is more closely represented by adiabatic conditions instead of isothermal.

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APPENDIX 1

Illustration of Non-Rigorous Mathematics

In Paper, "The Calculation of Pressure Drop in the Flow of Natural Gas Through Pipe"

Correct vertical flow equation — neglecting kinetic energy effect:

$$L = \int_{P_2}^{P_1} \frac{V\,(dP)}{1 + \dfrac{4 f u^2}{2 g D}}$$

This cannot be reduced to

$$L = \frac{\displaystyle\int_{P_2}^{P_1} V\,(dP)}{1 + \dfrac{4 f u^2}{2 g D}}$$

with the value of u determined by separate integration as the author performs in his Equations (14) through (16).

Correct gas flow equation — horizontal flow:

$$L = \int_{P_2}^{P_1} \frac{V\,(dP)}{\dfrac{4 f u^2}{2 g D}}$$

This cannot be reduced to

$$L = \frac{\displaystyle\int_{P_2}^{P_1} V\,(dP)}{\dfrac{4 f u^2}{2 g D}}$$

with the value of u determined by separate integration as the author performs in his Equations (14) through (16).

AUTHOR'S REPLY TO MR. MOSTELLER

The primary purpose of the paper was to present a procedure for calculating the sandface pressure of flowing gas wells. The other procedures available are those of the Bureau of Mines Monograph 7, and a recent paper by R. V. Smith.[3] In these equations compressibility is either ignored or a constant "effective" compressibility factor was used, the value of "effective" compressibility being left up to the judgment of the user. The calculation of static bottom hole pressure (which was overlooked by Mosteller), the equation for horizontal flow, and the isothermal horsepower equation were added only to illustrate other possible uses of the factors.

I would very much like to see a vertical flow equation mathematically rigorously derived involving the compressibility factor. The use of a constant velocity, whether an integrated average velocity or otherwise, in the energy loss term is not new, and if used as such, Equation (4) is correct as written since the term can then be removed from within the integral sign, for the same reason the so-called constant "effective" compressibility factor in other flow equations[1] was removed from within the integral sign. The use of a constant average velocity in the energy loss term is no more theoretically correct than assuming a constant "effective" compressibility, but if it provides us with a workable equation its assumption is justified. If the calculated results agree with the field measurements the equation is justified. Mosteller's comments concerning Table III are not valid. A gas man is interested in the absolute value of the sandface pressure, not the pressure drop, for purposes of calculating back pressure curves. Therefore, comparisons of the sandface pressures were made. It is the absolute pressure that determines the physical properties of the flowing fluid, not the pressure drop.

I am aware of Clinedinst's development of a horizontal flow equation. It does not assume an average velocity in the energy loss term and as such is more rigorous. It does assume a zero kinetic energy term. Its use is definitely preferred over Equations (32) or (33) of the paper. The Equations (32) and (33) have not been tested against field data. Clinedinst's development cannot be applied to vertical flow and result in a simple workable equation.

The assumption of a negligible kinetic energy term in the vertical flow of gas is valid. We have ample quantitative evidence to support this assumption. If Mosteller has quantitative evidence to the contrary, I would like to see it. Smith[3] has published some specific data, where, for the wells in question, the kinetic energy amounted to only 0.05 per cent of the total available energy.

Mosteller is concerned over the equation for calculating isothermal horsepower. I am familiar with the fact that actual gas compressions are polytropic and tend to approach adiabatic conditions. The equation presented is rigorous and represents the minimum value of the horsepower requirements that we would like to approach, adiabatic compression giving

us the maximum horsepower requirements. The adiabatic compression requirements of a real gas can be calculated very simply from an enthalpy-entropy diagram of the gas.[2] From a practical sense, the use of the isothermal horsepower equation may be somewhat limited, but that is no reason for not taking full cognizance of its existence, since it does represent the lower limit of horsepower requirement. Isothermal horsepower is extensively used in gas-lift calculations in calculating lift efficiencies.

$$L = \int_{P_2}^{P_1} \frac{V\,dP}{1 + \dfrac{4fv^2}{2g_c D}}$$

If we can assume v constant and equal to $\bar{v}$ by the same logic that Z was assumed to be constant and removed from within the integral sign, in other flow equations,[1] then:

$$L = \frac{\int_{P_2}^{P_1} V\,dP}{1 + \dfrac{4f\bar{v}^2}{2g_c D}}$$

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The Drift of Things

. . . as followed by **EDWARD H. ROBIE**
Secretary AIME

In this space this month we had expected to give our impressions of Mexico. Our plan of driving to the Fall Meeting in Mexico City, however, was unfortunately interrupted by an attack of bronchitis to which both the distaff and the mistaff sides of the family succumbed. As a result, several days were spent in Austin, Tex., instead of in Mexico City.

We did fly to Los Angeles for an interesting and well-attended Board meeting on October 25. It was a happy thought of Fay Libbey to take advantage of the Los Angeles meetings of the Mining Congress, of the Pacific Petroleum Chapter of AIME, and of our Southern California Section to schedule an extra Board meeting. Board meetings should be scattered around the country as much as is practical.

Also, we spent three interesting hours at the University of Texas, taking advantage of Harry Power's hospitality; enjoyed a dinner meeting until nearly 11 p.m. with some of the wheel horses (if there can be more than one wheel horse) of the Gulf Coast Section; and attended a similar luncheon meeting with 12 of the Delta Section in New Orleans. Professionally, we know less about what the petroleum boys do than about the activities of the mining and metals groups, but still we get a particular kick out of talking to oil men. In general, they are a younger group and have more ideas for changes in the Institute — things that we are paid to think of ourselves. Also, they are exceptionally friendly and hospitable. Further, they are critical of our mistakes, so keep us on our toes.

In New Orleans, we were especially indebted to Messrs. Petree and Hatfield of the Gulf Oil Co. for a thrilling airplane ride over the oil fields in the delta country of the Mississippi. Ol' Man Ribber has several mouths, but a mere look at a map gives but a poor idea of them. Water — in ponds, channels or marshes — covers almost the entire area, but under the water, even out to sea, are vast deposits of gas, oil and sulphur. Some of the gas is burning for lack of pipe lines to carry it to market, but the occasional flares are not too conspicuous. Tracks of the marsh buggies, man-made amphibians that travel over the marshes and swim when they come to open water, are a feature of much of the area.

No further offshore exploration is being done pending final determination of whether the Federal Government or the States are to have the right to lease the lands. We gather that it doesn't make too much difference to the oil companies, but they would like to have the question finally decided.

This little piece is being written in an old mansion not 100 ft from another famous river, the Suwannee in Florida. We suspected that the Suwannee River was an insignificant creek but find that, at least here in Old Town, it is a most impressive stream, maybe 200 or 300 yd wide and some 28 ft deep. Its banks are a jungle of sub-tropical vegetation, with pine and oak trees, festooned with gray Spanish moss. The ever-present moss lends a ghostly air of unreality to the scene.

Our trip will culminate in a couple of days in the phosphate country with a visit to our Florida Section at Lakeland. Then home.

Iran and the UN

Oil has long been a cause of international friction and the situation in Iran might easily have started a new war if cool heads had not prevailed. On paper, and following the old rules, the British had a right to own and operate their Iranian oil properties. Times are different now, however, and American oil companies, at least, have learned that exploitation of native populations leads to trouble. Sharing profits and assistance in the development of a country have proved a better policy, regardless of rights that might have been given in the past. Even so, Communistic influences are always ready to urge complete nationalization of any conspicuously successful foreign enterprise. Operations in a foreign country are always a gamble. In fact, with the United States itself about one-third socialized, capital is not safe anywhere any more. We say one-third because this is said to be approximately the portion of our national income which we perforce must pay to our Government.

Getting back to Iran and the Abadan refinery, it seems that this is exactly the type of problem that the United Nations should be set up to resolve. It is certainly a problem that concerns a foreign government or foreign nationals, as well as Iran. International law should state plainly what the respective rights are in a situation such as this, and the United Nations should have the power to enforce these rights. Only by such application of the idea of World Government can the United Nations develop into much more than a debating society.

No Red Ink This Year

The year-end financial reports are not available yet, of course, but we can say with some assurance that the Institute will finish 1951 with a sizable balance in the black. Not since 1941 has this occurred without transferring money from one or more of the funds. In this period, some $220,000 has thus been added to income to meet deficits. Practically no more money is available from such funds so it is fortunate that none will be needed.

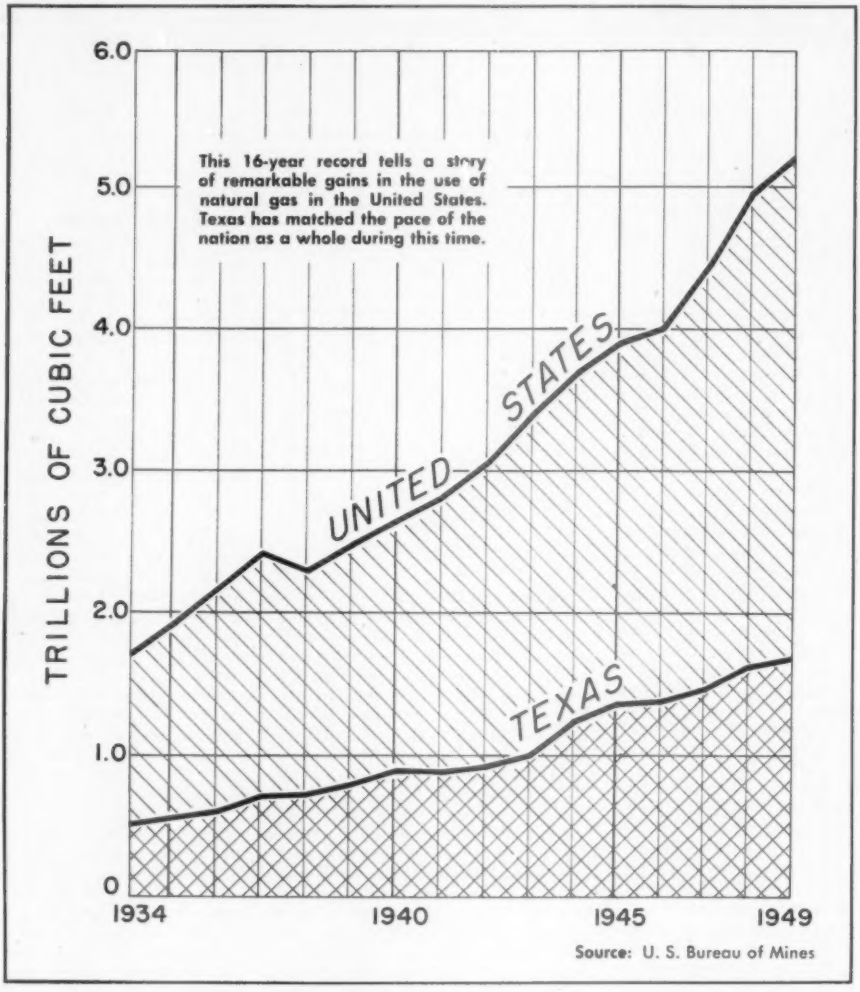
The money that has been used in founding three new magazines and building them up to a high standard is showing results. Increased advertising is largely responsible for the improved income. Unit expenses have increased with the continued decline in the value of the dollar, but rigid economy and the absence of a Directory in 1951 should hold expenses to about the 1950 figure.

Some of the 1951 profit is badly needed for new equipment at AIME headquarters and for an additional staff member. The rest should be used in making a start on repayment of the money borrowed from the reserve funds.

What of 1952? Barring a still further important drop in the value of the dollar — which is a dangerous assumption — the income next year should exceed considerably that of this year and expenses should not rise by as much. So the net should be even better next year.

What of 1953? That depends upon the referendum on dues, which will be decided by the members in the spring or summer of next year. We feel now that the future of the Institute would be adversely affected to a serious degree if the dues in 1953 went back to the 1922-1949 level. We also feel that by a further investment in the magazines and rehabilitation of the funds, there is an excellent possibility that much greater services can be extended to members five or ten years hence than at present; or that the present services can be given for less dues income. But that statement is made only if the value of the dollar does not decline further. This, we confess, is a big "if." ★ ★ ★

CONSUMPTION OF NATURAL GAS



An excerpt from our booklet, "Texas—First in Natural Gas" . . . presented for your information by our Oil and Gas Division.

44 Years of Service to the Southwest

The
SECOND NATIONAL
BANK OF HOUSTON
MAIN AT RUSK

CAPITAL AND SURPLUS TEN MILLION DOLLARS . . . MEMBER F.D.I.C.

GEORGE C. McGHEE, recently assistant secretary of state for Near Eastern, South Asian and African affairs, has been named American ambassador to Turkey by President Truman. Active in State Department affairs since 1942, McGhee was coordinator of aid to Greece and Turkey after World War II. A geologist and geophysicist, he is a Petroleum Branch, AIME, member.

AIME Announces 1952 Publications and Prices

Pursuant to Article X of the Bylaws of the AIME, the following information is hereby given as to the "conditions, prices, and terms under which the various classes of members and Student Associates, severally, shall be privileged to obtain publications of the Institute during the ensuing year."

Publications authorized for 1952 publication include the following: *Mining Engineering*, published monthly, containing material, including technical papers, of interest to those engaged in exploration, mining geology and geophysics, and metal, nonmetallic, and coal mining and beneficiation, and fuel technology. *The Journal of Metals*, published monthly, containing material, including technical papers, of interest to those engaged in nonferrous smelting and refining, iron and steel, and physical metallurgy. *The Journal of Petroleum Technology*, published monthly in Dallas, containing material, including technical papers, of interest to those engaged in petroleum and natural gas drilling, production and exploration.

Annual subscriptions to any one of the above journals will be provided all members in good standing without further charge. (A member ceases to be in good standing if current dues are not paid by April 1.) If more than one of the monthly journals is requested, $4 extra will be charged for an annual subscription, or 75c for single copies of regular issues and $1.50 for special issues. The nonmember subscription price for each journal is $8 in the Americas; foreign, $9. Student Associates will be entitled to the same privileges as members for all publications.

Three volumes of *Transactions* are authorized for 1952 publication, as follows: No. 190, Mining Branch; No. 191, Metals Branch; and No. 192, Petroleum Branch. These volumes will be available to members at $3.50 for a first copy if paid for in advance with dues; otherwise at the nonmember rate of $7 less 30 per cent; nonmembers $7 in the United States; foreign $7.50.

Special volumes now planned for publication in 1952 include the following: (1) *Open Hearth Proceedings*. Price to AIME members $7; nonmembers, $10. (2) *Blast Furnace, Coke Oven, and Raw Materials Proceedings*. AIME members $7; nonmembers $10. (3) *Electric Furnace Steel Proceedings*. AIME members $7; nonmembers $10. (4) *Symposium on Tube Producing Practice*. $3. (5) *Statistics of Oil and Gas Development and Production*, covering data for year 1950, free to members (except Student Associates); nonmembers $6. (6) *Statistics of Oil and Gas Development and Production*, covering data for year 1951, members $5, nonmembers $10.

If dues are paid subsequent to Jan. 31, back issues of Institute publications will be supplied only if adequate stocks are on hand. A member may not receive a volume of *Transactions*, or a special volume, in lieu of a monthly journal, free of charge on membership. Members in arrears for dues are not entitled to special members' prices for publications.

Rocky Mountain members may have their choice of an annual subscription to one of the monthly journals on request. ★ ★ ★

Sinclair Research Plan Enters Second Phase

With the approaching selection of the first invention to be processed under the Sinclair Plan, the advertising campaign sponsored by Sinclair Research Laboratories, Harvey, Ill., is entering its second phase.

Announced in April, the project provides the corporation's petroleum research facilities for free synthesizing of ideas for new or improved petroleum products. More than 10,000 responses have been received by the company in connection with the plan. The best ideas submitted by independent American inventors are now being sifted. ★

Charles M. Cooley Joins Mining Engineering Staff

Charles M. Cooley, assistant chief engineer of the Climax Molybdenum Co., Climax, Colo., has been engaged as assistant editor of *Mining Engineering*. Cooley reported for duty early in October. He received a degree in metallurgical engineering from the College of Mines and Metallurgy of the University of Texas at El Paso (now Texas Western) in 1947. He was on the staff of the school newspaper and magazine and was president of the school engineering society. He first worked with Colorado Fuel and Iron at Pueblo before joining the Climax organization three and one-half years ago. ★ ★ ★

Two Humble Fellowships Granted at Oklahoma U.

Two University of Oklahoma graduate students have been awarded Humble Oil and Refining Co. fellowships for the 1951-52 year, G. L. Cross, OU president, announced recently. They are Earl Graham Watkins, Oklahoma City, petroleum engineering recipient, and Jack Gordon Blythe, Wichita, Kan., geology winner. Basis of selection for

WATKINS

BLYTHE

the grants, which are presented annually, is outstanding promise, suitability for research in their fields and scholastic attainment.

Watkins was graduated from the OU college of engineering with a BS degree in 1951. He is an active member of the Petroleum Engineers' Club, Pi Epsilon Tau, honorary petroleum engineering fraternity, and Tau Beta Pi, honorary engineering group.

Now a candidate for the PhD degree in geology at the University of Oklahoma, Blythe holds a BA degree from the University of Wichita and an MS from Northwestern University. From January, 1949, to August, 1951, he served as an instructor in geology at the University of Wichita. During World War II, he was in the army air force for three years and was discharged as a staff sergent. ★ ★ ★

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 408 Trinity Universal Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded Y6279, Y6021, Y5908 and M-653 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

POSITIONS

♦ Recent graduate, chemical or lubrication engineer, for development and research work for machinery manufacturer. Salary, $3,120 - $3,640 a year. Location, upstate New York. Y6279.

♦ Sales engineer with oil field experience, to sell barite weighing material to drilling contractors and oil companies in Louisiana and Texas. Salary open. Y6021.

♦ Engineers. (a) Oil refinery process design engineer, 30-40, chemical or mechanical engineering graduate, with actual oil refinery distillation process design work on cracking plants or equivalent. Will supervise engineer and draftsmen in the design of all types of distillation units from flow plans and data. Must be able to discuss with oil refinery expert all phases of oil refinery design. Salary open. (b) Oil refinery field maintenance and construction superintendent, 30-60, with actual experience in the field working for an oil company or for a contractor who has contract work in an oil refinery performing the work listed — hiring and supervising all classes of mechanics and assigning them to oil refinery maintenance or construction as required. Salary open. Location, New York metropolitan area or Gulf Coast area, or both. Y5908.

♦ A southern university has an opening for a man to teach courses in petroleum and natural gas production engineering. It would be preferred that he have an MS degree but this will be waived in favor of adequate experience. Rank and salary will be based on the qualifications of the candidate. Code 536.

♦ (a) Research group leader and research engineer, 26-40. BS and preferably a PhD in physical chemistry, physics, petroleum engineering, or chemical engineering. Should have experience in reservoir mechanics research, or fluid flow research. Will be responsible for research program in multiphase flow and other aspects of reservoir mechanics.
(b) Research engineer, 26-40, BS and preferably an advanced degree in petroleum or mechanical engineering. Must be widely experienced in well completion practices. Will be responsible for research program in well completion practices and well mechanics.
(c) Research metallurgist, 26-40. BS and preferably advanced degree in metallurgical engineering. Should have experience with all types of laboratory apparatus for metallurgical study and experience in selecting materials for all types of services. Corrosion studies, materials selection and analysis of failures will constitute the bulk of the work. Salaries open. Location, Ponca City, Okla. State age, experience, education and salary desired in opening letter. Write direct to Personnel Records Division, Continental Oil Co., Ponca City, Okla.

♦ Geologists. The Carter Oil Co., a subsidiary of the Standard Oil Co. (N. J.) wishes to add geologists well-qualified for research on petroleum exploration to its permanent research staff at Tulsa, Okla. Geologists of broad general training but with special abilities in structural geology, stratigraphy, sedimentology, or micropaleontology are desired. Preference will be given to men with PhD degree or equivalent in training and experience. Send information to: Chief of Research, The Carter Oil Co., P.O. Box 801, Tulsa, Okla.

PERSONNEL

♦ Reservoir engineer, age 31, married, seven years' experience in lab, field and reservoir evaluation studies. Desire position with progressive independent as reservoir evaluation engineer. Code 158.

♦ Graduate petroleum engineer with 21 months' experience in materials and production, desires position as petroleum production engineer. Experience includes tool-dresser on spudder, completions, production, work-overs, equipment installations, equipment and production records, and office work. Presently employed as tool dresser on spudder for well completions and work overs. M-653.

Efficiency Procedures Recommended to Board

Recommendations for ways to improve the functioning of the New York headquarters office of AIME were made in a report presented to the Board of Directors at the Los Angeles meeting on Oct. 25. At the May 9, 1951, meeting of the Executive and Finance Committees, Gail Moulton had been asked to collaborate with Secretary E. H. Robie in obtaining an independent expert to review procedures at AIME headquarters. At the June 13 meeting of the board, it was reported that Herbert H. Vasoll, of the firm of Davies & Davies, certified public accountants, would make the study.

Highlights of the recommendations included (1) immediate purchase of a modern Addressograph machine to replace present equipment, at an estimated cost of $2,500. Such purchase was authorized by the board. (2) Installation of a punch card system for membership records, at an initial cost of some $600. (3) Purchase of a Pitney Bowes postage meter at a cost of about $600. This was also approved by the board for early action. (4) Engagement, from without the present organization, of a controller and business manager, who would have supervision over all functions of the business office. (5) Reorganization of the office into four primary departments, each supervised by one individual who in turn shall be responsible to the Secretary of the Institute.

These shall be: (a) Institute Activities Dept.—Convention planning, meeting arrangements, travel accommodations, membership control and promotion, special projects for the Secretary, public relations, and personnel. (b) Metals Branch Dept. — All activities pertaining to the Metals Branch of the Institute. (c) Publications Dept.—Editorial, Transactions, advertising, production, circulation promotion, publication of proceedings volumes, and any other Institute publications except those pertaining to the Petroleum Branch. (d) Business Office — Accounts, Addressograph, orders, purchasing, filing, and mailing.

At a meeting of the AIME Executive and Finance Committees, November 14, authorization was voted for the employment of a business manager as proposed. Other recommendations are being studied. ★ ★ ★

— It's a Fact —

America's 44,000,000 motorists paid an average of $82.36 in taxes to own and operate their vehicles last year.

Board Discusses Hocott Reorganization Proposal

A plan for reconstituting the Local Sections of the AIME, prepared by Claude R. Hocott, was presented for discussion to the Board at its meeting Oct. 25. It had previously been considered by the Petroleum Branch. The proposal would establish the Local Sections primarily on a Branch basis rather than on a strictly geographical basis as at present. Where more than one Branch is active in a local area an over-all Local Section might be established which would be divided into groups such as is the present organization of the Southern California Section. The respective Branches would then head up the Local Sections, instead of their being responsible to the national organization as at present.

Present appropriations to the Local Sections from the national treasury, totalling $10,000 per year, would no longer be made, thus saving this item of expense. A further $5,000 is currently spent in paying the expenses of delegates to the Annual Meeting. Branch Local Sections would be expected to be self-supporting, through the levying of dues or other means.

Considerable discussion followed presentation of the proposal but no action was taken. ★ ★ ★

Notice Given of Dues Payable Jan. 1, 1952

Pursuant to Article II, Section 2, of the bylaws of the AIME, notice is hereby given that dues for the year 1952 are payable Jan. 1 as follows: Members and Associate Members, $20; Junior Members for the first six years of Junior Membership, $12; Junior Members, thereafter, $17; Student Associates (including an annual subscription to a monthly journal), $4.50.

Mailing of dues bills began in October and will be completed before the end of the year. Prompt payment will assure uninterrupted receipt of the journal or journals desired in 1952. If, for any reason, a bill is not received within a reasonable time after the last mailing date, Dec. 31, headquarters should be notified. ★ ★ ★

— It's a Fact —

Taxpayers with net incomes of less than $10,000 get 86 per cent of the national income left after payment of federal income taxes. Those with net incomes of more than $10,000 get the other 14 per cent.

TEXAS A & M STUDENTS discuss recent developments in drilling practices and equipment with A. W. Thompson before a recent meeting of the Petroleum Engineering Club. Thompson, president of the American Association of Oilwell Drilling Contractors, was guest speaker. L to R are Julian Herring, president of the club; Thompson; and Joe Johnson, vice-president.

Petroleum Branch, AIME Student Affiliate Chapters Elect Officers, Plan Engineering Programs

AIME student affiliate organizations on campuses throughout the nation are now in the midst of their year's activities.

The University of Southern California Student Chapter is presently planning a Spring Meeting on the campus for students and men in industry. Officers serving the current term are James R. Grime, president; Autry D. Bull, vice-president; William Rieken, recording secretary; Dale E. Johnson, corresponding secretary; and Thomas Henderson, treasurer.

Programs on well logging, drilling practices and equipment, and gravel packing have been presented before the Petroleum Engineering Club at Texas A & M College this fall. W. H. Cook, division manager for Eastman Oil Well Survey Co. at Houston, is scheduled to be the guest speaker on Jan. 16.

Bob Hubbard is serving as president of the Petroleum Engineering Club at Oklahoma A & M College during this semester. Other officers are Bill Hubbard, vice-president; Will Zapf, secretary; Eldridge Manering, treasurer; and Garland Terrel, corresponding secretary.

New officers of the Petroleum Engineers' Club at the University of Oklahoma were elected recently. They are Bill Hise, Abilene, Tex., president; La Rue Watkins, Woodlawn, Ill., vice-president; Anne Warren, Shreveport, La., secretary-treasurer; William Maule, Flint, Mich., St. Pat's Council representative; Kamaleddin Ghahremani, Teheran, Iran, publicity chairman; Ralph Scroggins, Lenapah, Okla., entertainment chairman; and Dave Loveland, Stony Creek, Conn., and Al Thompson, Oklahoma City, Okla., open house and float co-chairmen. ★ ★ ★

Canadian Institute To Increase Dues

A 33⅓ per cent increase in dues has been voted by members of the Canadian Institute of Mining and Metallurgy, effective with 1952. The new dues are $16 for Members and Associates, and $12 for Junior Members and Junior Associates, except that a Junior Member may pay $5 for the three-year period immediately following graduation from an approved school. The vote was 1,140 for the increase, and 61 against. ★ ★ ★

Annual Business Meeting To Be Held February 19

The annual business meeting of the AIME will be held at the Hotel Statler, New York City, at 4 p.m. Feb. 19, 1952. Newly elected directors and officers assume their duties at this meeting. A report of the financial condition of the Institute will be made, as well as reports of the principal officers and standing committees. All AIME members are invited to attend. Immediately afterward, at 5 p.m., the new Board will meet in executive session. ★ ★ ★

Personals

A. C. POLK, JR., formerly assistant manager of Dowell Incorporated, has been named general manager. Also a member of the board of directors, he has been with Dowell since July, 1941. Before his promotion to assistant manager in 1948, Polk was located in Houston as district manager. Previously, he had been with Dowell in Levelland, Tex., Shreveport and Lafayette, La. He attended Rice Institute and the University of Oklahoma, where he majored in petroleum engineering.

+

D. K. MACKAY resigned as chief geologist, Arkansas Oil and Gas Co., El Dorado and is now geologist-engineer with the Federal Power Commission at Washington, D. C.

+

GEORGE S. MONKHOUSE is now with James A. Lewis Engineering, Inc., Evansville, Ind.

+

FLOYD J. SVOBODA has resigned from the National Supply Co. and is now associated with the Neosho Oil Co., Neosho Falls, Kans.

+

EVERETT S. WENGER is with J. R. Butler and Co., Houston.

+

NEIL B. STEUER has joined the exploration department of the Shell Oil Co., Wichita Falls, Tex.

+

J. J. ZORICHAK, formerly with the Rangely Engineering Committee, Rangely, Colo., is now with the Colorado Oil and Gas Conservation Commission, Denver.

+

JOHN C. PAPP has become reservoir engineer for The Texas Co., Erath, La. He had been with Transcontinental Gas Pipe Line Corp.

+

LEWIS B. HOWARD, JR., is now chief petroleum engineer for King & Heyne, Houston. He was formerly associated with the American Republics Corp.

+

J. R. UNDERWOOD, JR., is on military leave of absence from the Sohio Petroleum Co., Lafayette, La. He has been recalled to active duty by the Navy.

JOHN P. EVERETT, formerly with the University of Oklahoma, has joined the petroleum engineering department of the University of Kansas.

+

C. W. FLAGLER, previously associated with the Danish American Prospecting Co., Copenhagen, Denmark, has joined the Gulf Oil Corp., New York.

+

HOWARD M. PERDUE is now junior petroleum engineer for the Union Sulphur and Oil Corp., Lake Charles, La.

+

JAMES N. REEVES is now with the Pan American Production Co., Houston.

+

FRANK O. REUDELHUBER is senior chemical engineer for the Core Laboratories, Inc., Dallas.

+

GENE E. ROARK has become affiliated with James A. Lewis Engineering, Inc., Dallas.

JOHN L. CREIGH is associate petroleum engineer for Humble Oil and Refining Co., Houston.

+

CHARLES DAVID DAVIDSON, National Associated Petroleum Co., is now located at Owensboro, Ky. He was formerly with the Tulsa office.

+

LEONARD C. STEVENS is now employed by the Socony-Vacuum Exploration Co. in Calgary, Alberta, Canada. He will be in charge of engineering, drilling and production operations in western Canada. Stevens was formerly chief exploitation engineer for the Shell Caribbean Petroleum Co. in Maracaibo, Venezuela.

+

ROBERT H. SHEPARD, formerly with Superior Oil Co., has accepted the position of geologist with the Standard Oil of Texas, exploration division, Amarillo, Tex.

Proposed for Membership, Petroleum Branch

Total AIME membership on Oct. 31, 1951, was 17,313; in addition, 2,603 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Carless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mallison, John T. Sherman. Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. A. Clark, Jr.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend privileges but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; A, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

ARKANSAS

El Dorado — Burki, Arthur G. (M); Lassiter, Joseph B., Jr. (M) (R,C/S-S-M).

CALIFORNIA

Alameda — Carlson, Thomas C. (J) (C/S-S-J).
Beverly Hills — Aston, Charles A., Jr. (M).
Burbank — Seaman, William H. (M) (C/S-A-M).
Long Beach — Janke, Paul A. (M); Weeks, Harold E. (A).
Los Angeles — Lung, John D. (J) (C/S-S-J).
Ojai — Misbeek, Robert J. (J) (C/S-S-J).
San Francisco — Loeck, Robert E. (M) (R, C/S-J-M).
South Gate — Kazarian, Bob (J) (C/S-S-J); McGriff, John P. (J) (R,C/S-S-J).
Taft — Neblett, Lester T., Jr. (J) (C/S-S-J).
Tupman — Finical, Thomas N., Jr. (J).
Whittier — Wyman, Thomas S. (J) (C/S-S-J).

ILLINOIS

Centralia — Payne, Reed W. (J).

INDIANA

Gary — Ludwig, Norman C. (M).

LOUISIANA

New Orleans — Hailey, James W., Jr. (J) (R,C/S-S-J); Sheeler, James E. R. (M) (R).
Shreveport — Denham, Ralph R., Jr. (J).

MICHIGAN

Kalamazoo — Withrow, Harold J. (J).

NEW YORK

Jackson Heights — Boese, DeLyle B. (M).
Tuckahoe — Martin, James W. (M).
Wellsville — Thornton, Knight (M).

OKLAHOMA

Norman — Findeiss, Ted C. (M).
Shawnee — Cassingham, Robert W. (J).
Stillwater — Woods, Anson T. (C/S-S-J).
Tulsa — Bostick, Elton R. (J); Clark, Roscoe C., Jr. (M) (R,C/S-S-M); Ford, William T. (J); Harstine, John H. (J); Ireland, John D. (A).

TEXAS

Beeville — Narn, Marshall E. (J) (R,C/S-S-J); O'Bryan, John D., Jr. (J).
Clarkwood — Bartgis, Raymond (A).
Conroe — Davis, Lamar W., Jr. (M) (R,C/S-S-M).
Corpus Christi — Saner, Walter B. (J).
Corsicana — Bee, Dan A. (J) (C/S-S-J).
Dallas — Bendorf, Stanley G. (M) (R,C/S-J-M); Brown, Elton L. (J); Faulk, Joseph H. (M); Sikora, Vincent J. (J).
Fort Worth — Ellis, Harold Lantar, Jr. (J); Guffey, George C. (J); Hartman, Frederick H. (J); Matthews, Thomas K., II (J).
Houston — Brooks, Clyde S. (M); Lunstroth, Klaus (M); Osoba, Joseph S (J).
Lubbock — Whitis, Thurman S. (M).
Midland — Christie, Clarence E., Jr. (A); Dailey, Homer (M); Shields, Robert C. (J) (R, C/S-S-J).
Odem — Swanson, Charles H. (J).
Odessa — Gatlin, Carl (J) (C/S-S-J).
Refugio — Cullinan, Harvey James, Jr. (M).
San Antonio — Drews, Charles L. (J) (C/S-S-J).
Stilphee — Forney, Larry W. (J) (C/S-S-J).

VIRGINIA

Arlington — Hardison, Eugene D. (M).

WYOMING

Rock Springs — Myers, Robert G. (J) (R, C/S-S-J).

MEXICO

Mexico, D.F. — Head, Martin F., Jr. (M) (R, C/S-S-M).

JAPAN

Tokyo, Suginami-Ku — Niijima, Ryozo (M).

★ ★ ★

Nominating Committee For 1953 Slate Named

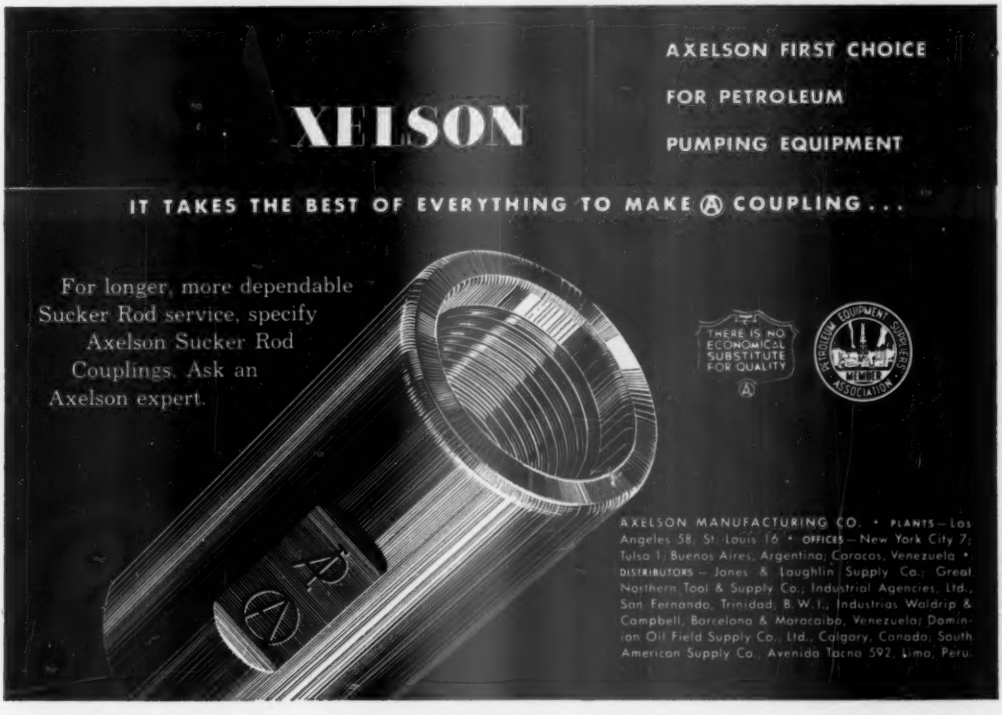
As provided in Article IX, Section 2, of the AIME Bylaws, the names and addresses of the Nominating Committee for Institute officers for 1953 are given below. In each case, the name in parentheses is that of the alternate, who will serve only in the absence of the principal at the meeting of the Committee.

Members designated by the Council of Section Delegates: Francis Cameron, St. Joseph Lead Co., 250 Park Ave., New York (Philip D. Wilson, Lehman Bros., 1 William St., New York); Henry A. Dierks, Glen Alden Coal Co., 631 Charles Ave., Kingston, Pa. (D. C. Helms, Lehigh Navigation & Coal Co., Lansford, Pa.); P. G. Spilsbury, Anaconda Copper Mining Co., Shoreham Hotel, Washington, D. C. (Thomas H. Miller, Bureau of Mines, Washington 25, D. C.); William A. Mueller, Ohio State University, Columbus (Harley Lee, Basic Refractories, Inc., 845 Hanna Bldg., Cleveland); Thomas M. Broderick, Calumet & Hecla Consolidated Copper Co., Calumet, Mich. (Raymond D. Satterly, Inland Steel Co., Box 360, Ishpeming, Mich.); Armor B. Martin, Montana Power Co., 40 E. Broadway, Butte (Tom Graham, Anaconda Copper Mining Co., Great Falls, Mont.); Drury A. Pifer, University of Washington, 505 Boston St., Seattle 9 (Albert H. Mellish, American Smelting & Refining Co., Tacoma, Wash.); George D. Dub, 1206 Pacific Mutual Bldg., Los Angeles 14, Calif. (alternate not selected); Edward M. Tittman, American Smelting & Refining Co., Box 1111, El Paso (Guy E. Ingersoll, Texas Western College, El Paso); S. S. Clarke, Tri-State Mines, Eagle-Picher Mining & Smelting Co., Cardin, Okla. (John W. Chandler, Eagle-Picher Mining & Smelting Co., First National Bank Bldg., Miami, Okla.).

Members designated by the Branch Councils: Edwin R. Price, Coal Properties, Inland Steel Co., Wheelwright, Ky. (J. Murray Riddell, dept. of mining engineering, Michigan College of Mining & Technology, Box 144, Houghton, Mich.); C. H. Behre, Jr., Geology Dept., Columbia University, New York 27 (Grover Holt, Cleveland Cliffs Iron Co.); John D. Sullivan, Battelle Memorial Institute, 505 King Ave., Columbus 1 (Maxwell Gensamer, dept. of metallurgy, Columbia University, New York); John E. Sherborne, Union Oil Co. of California, 1004 Summit Drive, Whittier, Calif. (Lloyd Elkins, Stanolind Oil & Gas Co., P.O. Box 591, Tulsa 2).

Members designated by President Peirce: John R. Suman, Chairman, Standard Oil Co. (N.J.), 30 Rockefeller Plaza, New York 20 (Henry T. Mudd, 1206 Pacific Mutual Bldg., Los Angeles, Calif.); principal to be named (George P. Halliwell, H. Kramer & Co., 1339-45 W. 21st St., Chicago 8); H. M. Griffith, The Steel Co. of Canada, Ltd., Hamilton, Ont., Canada (C. D. King, U. S. Steel Corp. (Del.), 436 Seventh Ave., Pittsburgh).

The Committee will welcome suggestions for the official slate for 1953. The following offices are to be filled: President-Elect for 1953 (president for 1954), two Vice-Presidents, and six other Directors. The terms of the following Directors eligible for reelection expire in February, 1953: D. H. McLaughlin, R. W. Thomas, H. Decker, F. B. Foley, E. C. Meagher, C. V. Millikan, G. F. Moulton, and Howard I. Young. ★ ★ ★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Book Reviews

The following books are available in the Engineering Societies Library, and may be borrowed by mail by AIME members for a small handling charge. The library also prepares bibliographies and translations, and provides search, photostat and microfilm services. Address inquiries to Ralph H. Phelps, Director, Engineering Societies Library, 29 West 39th St., New York 18, N. Y.

Glossary of Petroleum Terms

Institute of Petroleum, Manson House, 26 Portland Place, London, W.1, 1951. 16 pp., 8¼ x 5½ in., paper, 1s.

Definitions are given for 117 terms dealing mainly with the more widely-known petroleum products. As simple language as possible has been used for the benefit of the non-technical reader. Subsequent lists are to be published covering more specialized terms used in the various fields of the petroleum industry.

Formation of Mineral Deposits

By A. M. Bateman. John Wiley and Sons, New York; Chapman and Hall, Ltd., London, 1951. 371 pp., illus., diagrs., charts, maps, tables, 9¼ x 6 in., linen, $5.50.

This new text discusses, with a minimum of technical language, the primary sources of mineral substances, how they came to be moved to their present sites, the agents of transportation, how they were deposited or concentrated into economic deposits, and how they became affected by weathering or other subsequent geological processes. Exploration, exploitation, and the distribution of mineral deposits are also covered. Much of the material has been taken from a previous, more extensive and technical book by the same author. ★ ★ ★

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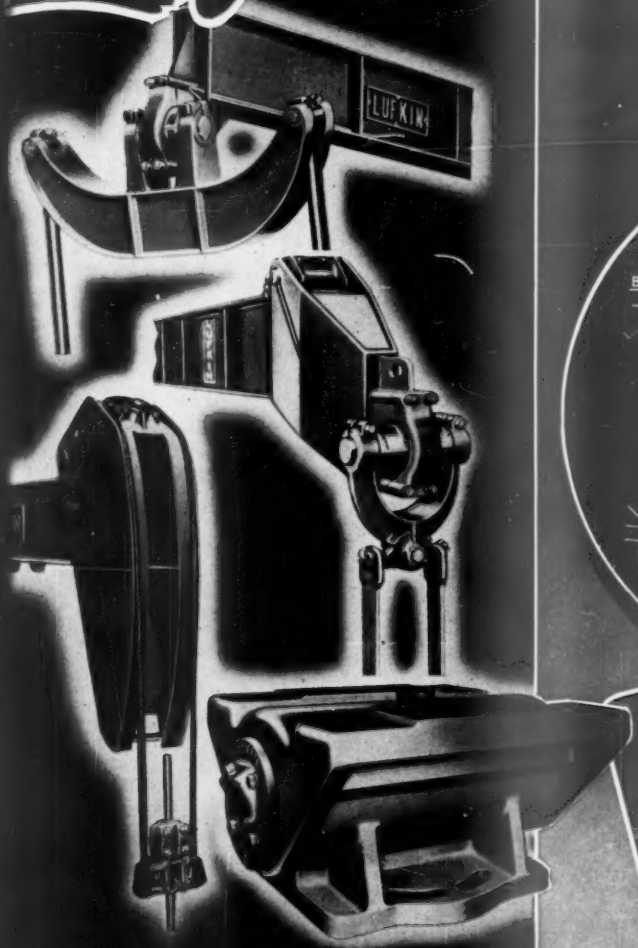

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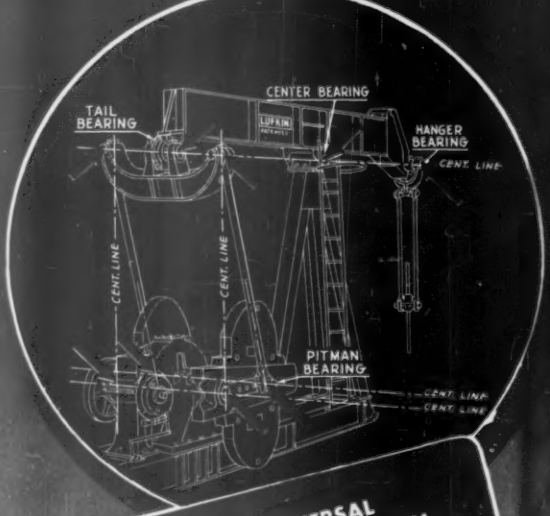

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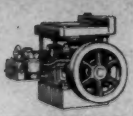

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